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ACTIVE BEACON COLLISION AVOIDANCE LOGIC EVALUATION: VOLUME I. MODE C EQUIPPED (ATCRBS) THREAT PHASE.

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DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

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Prepared for

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16. Abstract

The purpose of this project was to evaluate and refine the April 1979 version of the Beacon Collision Avoidance System (BCAS) logic prior to Active BCAS prototype flight testing. The April 1979 version of the BCAS logic added changes to support multiple aircraft resolution, conflict indicator register interfacing, and new surveillance function interfacing. The first phase of the evaluation was conducted from April 1979 to September 1979. This phase evaluated logic performance against mode C equipped (ATCRBS) threats. The evaluation identified modifications which could improve logic performance. Interim improvements have been made to the vertical tracker. The modifications improve (1) command sense choice logic performance for ATCRBS threats (by using greater dependence on current relative vertical position), (2) resolution performance (by modifying ATCRBS-threat sense choice logic), and (3) vertical speed limit (VSL) alarm performance. Generally, good protection was provided by the BCAS logic against abrupt horizontal maneuvers by ATCRBS threats. VSL alarms generated sufficient vertical separation when the BCAS aircraft's vertical rate was above 1,000 feet per minute. Below 1,000 feet per minute, tracker noise often resulted in a transition from VSL alarms to positive or negative BCAS maneuver advisories. Before proceeding to subsequent phases of the evaluation, large portions of the logic modifications that were identified in this report became permanent algorithm changes.

17. Key Words
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LIST OF ABBREVIATIONS AND ACRONYMS

ACAS - Airborne Collision Avoidance System

Altimeter Correspondence Error - The error due to improper mode C altitude encoding

Alpha - The altitude tracking weighting constant in an Alpha-Beta tracking system

ASA - Aircraft separation assurance

ATARS - Automatic Traffic Advisory and Resolution Service

ATC - air traffic control

ATCRBS - Air Traffic Control Radar Beacon System

ATCSF - Air Traffic Control Simulation Facility

BCAS - Beacon Collision Avoidance System

Beta - The altitude rate tracking weighting constant in an Alpha-Beta tracking system

CIR - Conflict Indicator Register

CSC - Computer Sciences Corporation

DR&A - Data reduction and analysis

FTEG - Fast-Time Encounter Generator

g - Acceleration due to gravity, 32.16 feet per sec^2

ID - Aircraft identification

IFR - Instrument Flight Rules

ILS - Instrument Landing System

IPD - Intruder positional data (proximity warning indication)

Mode C - Aircraft encoding altimeter capability

PPD - Partial positional data (proximity warning indication containing only range and altitude of threat)

VFR - Visual flight rules

VSL - Vertical speed limit

LIST OF BCAS ALGORITHM TERMS

A	Absolute altitude separation
ADOT	Relative tracked altitude rate
ALIM	Altitude threshold for choice of positive or negative commands (470 feet)
ALPC	Threshold for high altitude threat declaration (18,000 feet)
ALUH	Threshold for ultrahigh altitude threat declaration (29,000 feet)
ASEPH	High altitude threshold for choice of positive or negative commands (670 feet)
ASEPU	Ultrahigh altitude threshold for choice of positive or negative command (770 feet)
CLMRT	Assumed BCAS climb escape rate (16.67 feet per second)
CMDSAV	Previous command selected array
Command Sense	The vertical direction of a BCAS command
COMP Function	The function in the coordination logic that forms the complement of a threat message
CPA	Closest point of approach
D Field	Own maneuver intent field in the CIR
DESRT	Assumed BCAS descent escape rate (-25 feet per second)
DMOD	Modification distance applied to tracked range (0.1, 0.3, or 1 nautical mile
DRACT	Detection and resolution module
DRPFLG	Flag indicating need to drop the command
EQ	Flag indicating intruder is BCAS equipped
INDEX	Performance level for selection of threat logic parameters
KHIT	Intruder detection counter
MTENT	Intruder's indicated maneuver intent
OWNTENT	Own aircraft maneuver intent for specified threat
R	Tracked range to intruder
RD	Tracked range rate

RZ	Tracked relative altitude
RZD	Tracked relative altitude rate
SLEVEL	Performance level value received from air traffic control
T1	Estimated delay time for responding to vertical speed limit command
TAU	Ratio of distance to rate of change
TAUR	Modified range tau
TAUV	Vertical tau (time to coaltitude)
TCUR	Current time for internal clock
TCMD	Time latest command was selected
TDC	Time to establish climb escape rate
TDD	Time to establish descent escape rate
TDROP	Time without reported data to drop an intruder
TESC	Anticipated maneuver time before closest approach
TRIACT	Intruder tracking module
TROACT	Own aircraft tracking module
TRTRU	True range tau (-range/range rate)
TSSC	Length of time of maneuvering at climb escape rate
TSSD	Length of time of maneuvering at descent escape rate
TVPCMD	Look-ahead time for altitude detection (40 to 45 seconds)
TVPESC	Look-ahead time for altitude resolution (30 to 35 seconds)
TV1	Time delay provision for response to commands (8 seconds)
TZ3	Time required to achieve assumed escape rate
VACCEL	Assumed escape acceleration (8 feet per sec^2)
V1	Calculated vertical rate (feet per second) for own aircraft to achieve vertical separation of ALIM feet at closet point of approach
VLIM	Selected magnitude of VSL
VMD	Projected vetical miss distance

VSL	Vertical speed limit command
ZDCLM	Achievable climb rate
ZDDES	Achievable descent rate
ZDINT YDINT XDINT	Tracked intruder's velocity coordinates
ZDOWN	Tracked own altitude rate
ZINT	Intruder tracked altitude
ZMPCLM	Predicted vertical miss distance after climb command
ZMPDES	Predicted vertical miss distance after descent command
ZOWN	Tracked own altitude
ZPINT	Predicted altitude for unequipped intruder
ZPOWN	Predicted own altitude at CPA when TRTRU $\leq$ 8 seconds
ZTHR	Immediate altitude threshold used in threat detection (750 feet)
ZTHRH	Immediate altitude threshold used in threat detection in high altitude airspace (850 feet)
ZTHRU	Immediate altitude threshold used in threat detection in ultrahigh altitude airspace (950 feet)

INTRODUCTION

PURPOSE AND SCOPE.

This document describes the results of research conducted to evaluate the resolution performance of the Active Beacon Collision Avoidance System (BCAS) logic (reference 1). A fast-time simulation program was developed to generate paired and multiple aircraft encounter scenarios and measure the performance of BCAS against unequipped encounters. The test bed that resulted, the Fast-Time Encounter Generator (FTEG), provides the means of rapidly evaluating BCAS conflict resolution performance across a wide variety of conflict geometries, speeds, crossing angles, and experimental conditions. A description of the FTEG is presented in appendix A of this report. The research reported in this document is not intended to replace live flight testing of the Active BCAS logic. The research is directed toward developing and validating improvements to the logic prior to the more expensive and time-consuming flight testing. These fast-time evaluations also augment live flight tests by providing a baseline performance standard against which Active BCAS flight results can be compared.

The evaluation measures the performance of the Active BCAS collision avoidance logic. More than 15,000 aircraft conflicts were simulated during all phases of the evaluation. Only the BCAS air-to-air coordination procedures were simulated; the BCAS/Automatic Traffic Advisory and Resolution Service (ATARS) logic interfaces were not coded for this evaluation. Throughout the report the phrase, BCAS command, is synonomous to BCAS maneuver advisory, own aircraft refers to the BCAS equipped aircraft, and intruder refers to the threat aircraft.

BACKGROUND.

On three separate occasions, real-time simulations of BCAS logic have been conducted at the Federal Aviation Administration (FAA) Technical Center using the Air Traffic Control Simulation Facility (ATCSF). The first two evaluated the impact of the Full BCAS logic on the air traffic controller in two different terminal air traffic control (ATC) environments. The terminal environments simulated were the Chicago (O'Hare) and Knoxville (McGhee-Tyson) terminal areas. The results of these simulations were reported in references 2 and 3. The third simulation in the ATCSF assessed the impact of an interim version of the Active BCAS on the controller in the Knoxville terminal area. The results of this prototype testing are reported in reference 4. The interim Active BCAS logic was also used in the air carrier simulations conducted by Aeronautical Radio, Incorporated (reference 5).

OBJECTIVES.

The primary objective of the research documented in this report is to test and evaluate the performance of the new Active BCAS collision avoidance algorithms against mode C equipped (ATCRBS) threats. Some other objectives of the research are:

1. To assess the ability of BCAS to generate adequate separation in a multiple encounter environment.

2. To identify scenario conditions which result in inadequate BCAS-generated separation.

3. To identify scenario conditions which cause BCAS to issue oscillating command sequences.

4. To assess the impact of realistic Active BCAS measurement errors on BCAS performance.

5. To evaluate BCAS-to-BCAS coordination procedures and BCAS-generated separation during encounters with BCAS equipped intruders.

6. [illegible] changes which improve code efficiency.

[illegible]

[illegible] is conducted in four sequential phases. [illegible] approach to the overall logic evaluation. [illegible] unequipped intruders (ATCRBS threats) is [illegible] coordination protocol logic for equipped [illegible] procedures have to be checked prior [illegible] resolution logic. The division of the [illegible] allows for the updating of the collision [illegible] manner. Logic deficiencies detected [illegible] proceeding to the next phase. This limits [illegible] subsequent phases. The results of [illegible] phase, is presented in this report. The [illegible] in subsequent volumes.

[illegible] phase of the evaluation activities assesses [illegible] performance for unequipped intruders. [illegible] against unequipped intruders in simple [illegible] designed to become progressively more complex. [illegible] unequipped intruder performance includes [illegible] BCAS aircraft and the intruder are maneuvering [illegible]

Although [illegible] Register (CIR) is not required to coordinate commands in this phase, the ability of the CIR to properly locate and correlate ATCRBS threat [illegible] data is subjected to a thorough review.

EQUIPPED THREAT PHASE. The second stage of the research investigates Active BCAS performance for BCAS equipped threats. The coordination logic must function properly in this stage. As in the initial phase, equipped intruder performance is first measured against simple linear encounters. The complexity is then increased to include scenarios in which both aircraft are maneuvering vertically and/or horizontally.

MULTIPLE INTRUDER PHASE. The error-free data analysis activities culminate in this phase. In the multiple intruder phase, performance is measured in a two intruder (three aircraft) environment. The equipped status of the intruders is varied so that all possible intruder equipment combinations are analyzed. This phase stresses the threat correlation and multiple aircraft conflict resolution logic. The results from all the phases form the basis for comparison of the error degraded logic performance in the final phase.

ERROR DEGRADED PERFORMANCE PHASE. The final phase calls for the evaluation of the Active BCAS collision avoidance algorithm performance in an error-degraded environment. The logic input measures of altitude and range are degraded through the auto-regressive modeling of range measurement and own and intruder altitude measurement errors (reference 6). Additionally, the impact of delayed intruder track establishment and missing intruder track reports is analyzed. A sensitivity study identifies how these error characteristics affect the BCAS logic.

SUMMARY OF RESULTS

The vertical tracker within the Active BCAS logic is an $\alpha - \beta$ vertical tracker. During steady-state climbs and descents, the cyclic rate errors in the rate tracking cycle caused the occasional incorrect command sense choices. That is, on these occasions, the maneuver sense selected did not provide as much separation as the opposite sense would have. The probability of incorrect command sense choice was most significant for own aircraft or intruder aircraft vertical rates below 1,500 feet per minute (ft/min). A reduction in the β parameter from 0.15 to 0.10 and subsequently to 0.05 reduced the rate error magnitudes. Additions to the unequipped intruder sense choice logic which places more emphasis on current relative vertical position rather than vertical rate, further reduced the probability of incorrect sense choice. However, incorrect sense choices may still occur, especially when sense selection occurs during vertical accelerations by an unequipped threat. A more responsive nonlinear vertical tracker being developed by Lincoln Laboratories should provide for better intruder sense choice performance during periods of vertical acceleration by the unequipped threat.

Altitude-based parameters which identify performance level thresholds (ALIM, ZDTHR, and the set ZTHR, ZTHRH, and ZTHRU) are not always set properly. Logic changes identified in this report will ensure that the thresholds in BCAS-to-BCAS conflicts representing the larger threat volumes will be selected when two BCAS aircraft are in conflict but operating at different performance levels.

Several flaws were detected in the unequipped intruder sense choice logic. The logic does not allow for acceleration delay for a BCAS aircraft's response to a BCAS alarm. In determining projected vertical separation, following response to the BCAS alarm, the unequipped sense choice logic assumes the 1,000-ft/min climb (-1,500-ft/min descent) escape rate can be obtained 8 seconds after the BCAS alarm independent of the vertical rate of the BCAS aircraft at time of the alarm. Extensive logic additions to model response acceleration have corrected this deficiency.

The sense choice decision was based on an assumed descent escape rate of -1,500 ft/min and a climb escape rate of 1,000 ft/min. This difference caused an imbalance in the sense choice logic. Descents were favored even when both aircraft were level with BCAS above the intruder. For slow range rate geometries (near tail chase encounter condition), the BCAS aircraft could be more than 400 feet above the intruder (both in level flight) and still receive a descent command. This condition has been corrected by balancing the sense choice logic (presumed descent escape rate = climb rate = 1,000 ft/min) and by limiting the look-ahead time to closest point to approach (CPA) in low range rate conditions.

Although intruder detection may occur quite early, the intruder may not be declared a threat until both range and altitude criteria are met. This can lead to threat declaration occurring within 5 seconds of CPA when nearly sufficient altitude separation exists. This late threat declaration occasionally causes wrong sense choices to occur because the anticipated time to CPA following maneuver response (TESC) is negative. Logic changes have been added which permit sense selection based on relative vertical position when TESC is negative.

Unnecessary alarms resulted when either the own or intruder aircraft was established in a descent or climb and more than 2-mile horizontal separation existed at CPA.

Although Active BCAS cannot project horizontal separation at CPA due to the lack of bearing information, a projected range at the time of predicted coaltitude can be obtained. This logic has been added to eliminate some of the unnecessary alarms that occurred during the evaluation.

During some encounters with a vertically accelerating unequipped threat, small vertical separations at CPA were observed. The incorporation of the nonlinear vertical tracker and the display of partial positional data (intruder range and altitude information) should reduce the severity of this problem.

Analysis of the vertical speed limit (VSL) command performance indicated sufficient separation was generated with VSL commands when the BCAS aircraft's rate was above 1,000 ft/min. Logic changes were made so that VSL command magnitude could not change every logic cycle. Once a VSL magnitude is selected, it will remain displayed for a minimum of 5 seconds, the same minimum time period as any of the other alarms. Unnecessary VSL alarms occurred in the presence of large horizontal miss distances at CPA. The occurrence of such alarms will be reduced with the addition of the determination of projected range at predicted time of CPA.

The current VSL magnitude set is 500, 1,000, and 2,000 ft/min. An investigation of the VSL magnitude set 1,000, 2,000, and 4,000 ft/min indicated that the BCAS aircraft deviated less from its vertical profile but only at the cost of an increase in the number of transitions in the magnitude of the VSL alarms. As a result, a change in the magnitude of the VSL alarms is not recommended.

Once the previously noted logic deficiencies were corrected, an extensive analysis of the logic performance was made. In general, Active BCAS provided sufficient separation from ATCRBS threats in level flight. Encounter resolution performance, when either or both aircraft were in constant rate climbs or descent, was good. Active BCAS performance was good against ATCRBS threats which began with realistic initial separations and then made abrupt horizontal maneuvers. Separation assurance systems in general, and Active BCAS in particular, can provide only limited protection when intruders abruptly maneuver in the vertical plane. This is especially true with the small initial vertical separations that can occur in today's air traffic control system.

A chronology of logic deficiencies and the logic modifications required to correct the deficiencies is presented in appendix B. The appendix refers the reader to specific page numbers in this report where each logic deficiency is described in

detail. Throughout the report, use is made of BCAS algorithm terms as they exist in the documented logic. The definitions of these terms are included in the list of BCAS algorithm terms.

EVALUATION PROCEDURES

GENERAL.

The evaluation of Active BCAS requires the interface of two highly interrelated algorithms. The first is the FTEG or simulation algorithm which operates in fast time and performs the data reduction and reporting tasks. The second is the BCAS or technological algorithm which represents the Aircraft Separation Assurance (ASA) System under evaluation. The description of the BCAS algorithm and interface software is summarized in appendix C. The FTEG controls the execution of the BCAS algorithm and several subprograms which model the flight profiles and aircraft as they interact with BCAS. The FTEG supports the reconstruction of all encounters identifying pertinent BCAS variables, commands issued, and aircraft positions on a logic cycle basis. These data specify the performance characteristics of BCAS for defined scenario conditions and allow an evaluation based on a required set of performance standards. Recommendations are made for logic changes based on the encounter conditions which cause substandard BCAS performance.

BCAS PERFORMANCE STANDARDS.

The basic BCAS performance standards used in this evaluation were:

1. BCAS advisories, when followed, should generate separation between conflicting aircraft in a timely fashion to ensure at least 300 feet of vertical separation at the closest point of approach. For conflicts with a single intruder, BCAS should not reduce the already existing separation between aircraft at CPA.

2. A particular aircraft should not receive a set of contradictory commands. The commands should not oscillate (e.g., alternating CLIMB and DESCEND commands).

3. All conflicting aircraft (including multiaircraft encounters) should receive mutually consistent command sets. Commands issued to any one aircraft should be compatible with commands issued to other aircraft in the same conflict.

4. BCAS commands should not generate unnecessary separation. Aircraft which are properly separated using controlled VFR separation standards should not receive commands which require pilot action to increase separation.

LOGIC TEST AND SOFTWARE CONTROL.

The FTEG/BCAS test system software is resident on two separate peripheral memory devices to facilitate BCAS logic evaluation and BCAS logic modification validation. One FTEG/BCAS test system is designated as the debug system. The debug system permits the output of desired intermediate results of BCAS calculations to facilitate functional debugging of the algorithm. Proposed logic modifications resulting from the FTEG/BCAS simulations are initially implemented in the debug system for validation of the modified logic. The other FTEG/BCAS system reflects the current stage of the BCAS logic and is considered the working system. All BCAS

analytical efforts are supported by the FTEG/BCAS working system. No modifications are implemented to the BCAS working system until the modification has been tested on the debug system and coordinated with the Systems Research and Development Service (SRDS) and MITRE personnel.

Logic stages of the BCAS working system are chronologically stored on a peripheral memory device to create a "history" of the BCAS working system. The BCAS working system history enables the user to (1) identify the logic stage used in previous FTEG/BCAS simulations and (2) reconstruct previous simulations.

A formalized procedure adopted by the FAA Technical Center for modifying the BCAS logic was followed during the BCAS algorithm evaluation:

1. Identify problem area by utilizing the BCAS working system.

2. Document the problem.

3. Recommend solution by utilizing the BCAS debug system to ensure solution efficiency.

4. Inform SRDS and MITRE via memorandum or a formal briefing of the problem and the proposed solution.

5. Coordinate logic changes with SRDS and MITRE.

6. If SRDS and MITRE agree that a solution is necessary, but do not concur with the proposed solution and do not provide an alternative solution, step 3 is exercised again.

7. If SRDS or MITRE suggest an alternative solution, step 9 is performed using their solution.

8. If SRDS and MITRE concur with the recommendation, step 9 is performed with proposed solution.

9. Modify debug system to reflect proposed solution and perform simulations to ensure the efficiency of the solution.

10. If the proposed solution efficiency is verified in step 9, the previous BCAS working system is stored and dated on the BCAS chronology memory device. The current working system is updated to create a new working system.

DESCRIPTION OF ACTIVE BCAS.

The BCAS algorithm uses range and altitude track data to detect all potential conflicts. (Threat criteria are defined in appendix C.) The BCAS algorithm then resolves the conflicts through the issuance of vertical commands. The sense of the command (climb or descend) is originally selected when an intruder aircraft enters the own aircraft's protected zone. The sense calculation is dependent upon the BCAS equipage of the intruder and other scenario conditions and remains constant throughout the sequence of commands generated by the BCAS algorithm to resolve the conflict. Once the sense of command is chosen, the type of command (positive, negative, or vertical speed limit) is selected. The list of available active BCAS commands is shown in table 1. Additionally, the BCAS aircraft maneuver response used in the simulation is shown.

Before selecting the type of command, the resolution algorithm considers the projected vertical miss distance at the closest point of approach, the projected time to closest point of approach (TAU), and the own aircraft's and intruder's altitude rates.

TABLE 1. ACTIVE BCAS COMMANDS

Command	Response	Sense
Don't Climb	If climbing - stop climbing; otherwise continue current vertical profile or descend.	Descend
Don't Descend	If descending - stop climbing; otherwise continue current vertical profile or climb.	Climb
Climb	Initiate climb maneuver. If currently climbing, increase rate of climb, if possible.	Climb
Descend	Initiate descent maneuver. If currently descending, increase rate of descent, if possible.	Descend
Limit climb to (5,000, 1,000, 2,000 ft/min)	If climb rate is above display limit climb rate, reduce rate to displayed rate. Otherwise, continue current vertical rate or descend.	Descend
Limit Descent to (500, 1,000, 2,000 ft/min)	If magnitude of descent rate is above displayed rate, reduce magnitude to displayed rate. Otherwise, continue current vertical rate or climb.	Climb

The BCAS command selected is a combination of the sense and type of command. Coordination of the maneuver intent is done to ensure command compatability between conflicting BCAS equipped aircraft. In the active BCAS logic evaluated here, this procedure makes use of the CIR to exchange aircraft identity and maneuver intent information between the conflicting BCAS equipped aircraft. The CIR was also created to coordinate conflict resolution when BCAS and ATARS coexist. When it is determined that a command is required due to a particular threat, the BCAS coordination logic ensures:

1. The new command is compatible with the previous entries in the CIR. Hence, the new command and the commands already present in the CIR can all be simultaneously obeyed. The BCAS multiple aircraft logic may reselect the commands if necessary.

2. The new command is compatible with the intruder aircraft's intent. Coordination is necessary to prevent own and intruder aircraft from choosing incompatible maneuvers.

The coordination procedure is repeated every logic cycle for the duration of the encounter. Once compatible senses are selected, they will not change during the encounter unless an intruder is dropped or a new one is added. Whenever more than one threat exists for own aircraft, the multiple aircraft logic may reselect the BCAS command. The multiple aircraft logic will generate positive commands if the BCAS aircraft is the top or bottom aircraft in a multiple aircraft conflict. If the BCAS aircraft is not the top or bottom aircraft, the multiple aircraft logic changes any positive command to a negative command.

EVALUATION RESULTS FOR ATCRBS THREATS

The evaluation of Active BCAS performance for ATCRBS threats began in June 1979. This evaluation activity lasted 4 months. Deficiencies in logic detected in the early stages were corrected before obtaining general measures of BCAS performance for ATCRBS threats.

PRERUN ALGORITHM ANALYSIS.

A preliminary analysis of the baseline collision avoidance logic (reference 1) was made prior to beginning the evaluation phases. This analysis identified several specific problems in the documentation of the original logic. The problems were described in several memoranda. All logic documentation problems were resolved prior to beginning the first evaluation phase. The revisions of the documentation describing the collision avoidance logic permitted a more highly controlled baseline logic to exist.

At the end of this prerun analysis period, a list of the unresolved logic problems was prepared. This list was used to identify where the test and evaluation collision avoidance logic differed from the logic described in reference 1.

One difference in the evaluation logic was the coding of the COMP function. The COMP function is found in the coordination logic, COORD, and is used (1) to form the CIR D Field (or DRACT OWNTENT) array complements and (2) to set the complement bit. The following coding was used in the evaluation logic to support the COMP function:

IF CMDTRT(i) = 10 bit complemented Threat message i = 1,2,...,10

then

CMDTRT(i) = Threat message bit i   i = 1,2...,6,8,9

the sense bit,

CMDTRT(7) = |Threat message bit (7) -1|

and complement flag bit

CMDTRT(10) = 1.

This coding of CMDTRT (the complemented threat message) was consistent with threat message format requirements in other coordination logic modules such as RCV and COMPATIBLE.

Another addition to the reference 1 logic that was made prior to the evaluation tests was the initial entry of the threat track block ATCRBS data into the CIR. Figure 1 presents the addition in the COORD module to initiate the threat block.

The last modification in the evaluation logic and the logic documented in reference 1 was the location of the logic which set the high and ultrahigh altitude performance level parameters. For a pair of aircraft which are both BCAS equipped, the threat volume must be set to the larger of the two individual threat volumes of the aircraft in the pair. The baseline logic would not permit this since the special threat volume parameters would be set in the own aircraft tracking module TROACT. This module has no knowledge of intruder altitude. To offset this problem, the setting of the high altitude and ultrahigh altitude threat volume parameters was moved to DRACT, the detection and resolution module. Since the threat altitude ZINT is available in this module, the size of the threat volume could properly be set to the larger of the two individual threat volumes. The logic to support this evaluation system change is shown in figure 2. All prerun algorithm changes eventually became permanent modifications to the baseline logic.

BCAS PERFORMANCE AGAINST ATCRBS THREATS

The description of Active BCAS performance against ATCRBS threats is divided into six major areas:

1. Tracker Performance for Unequipped Threats
2. Unequipped Intruder Sense Choice Logic Performance
3. Vertical Acceleration Performance
4. Advantages of Partial Positional Data
5. Vertical Speed Limit Performance
6. General Performance

Logic deficiencies discovered during testing in one area were corrected prior to proceeding with subsequent testing.

TRACKER PERFORMANCE FOR UNEQUIPPED THREATS.

The vertical tracker algorithm outlined in MITRE's April 1979 version of the Active BCAS logic (reference 1) was evaluated in detail from May through July 1979. Errors associated with the vertical rate tracker had an adverse impact on conflict resolution involving unequipped aircraft. Problems resulting from poor tracker performance were identified and briefed to SRDS (ARD-242) and MITRE Corporation. In August 1979, MITRE Corporation released a memorandum detailing modifications to

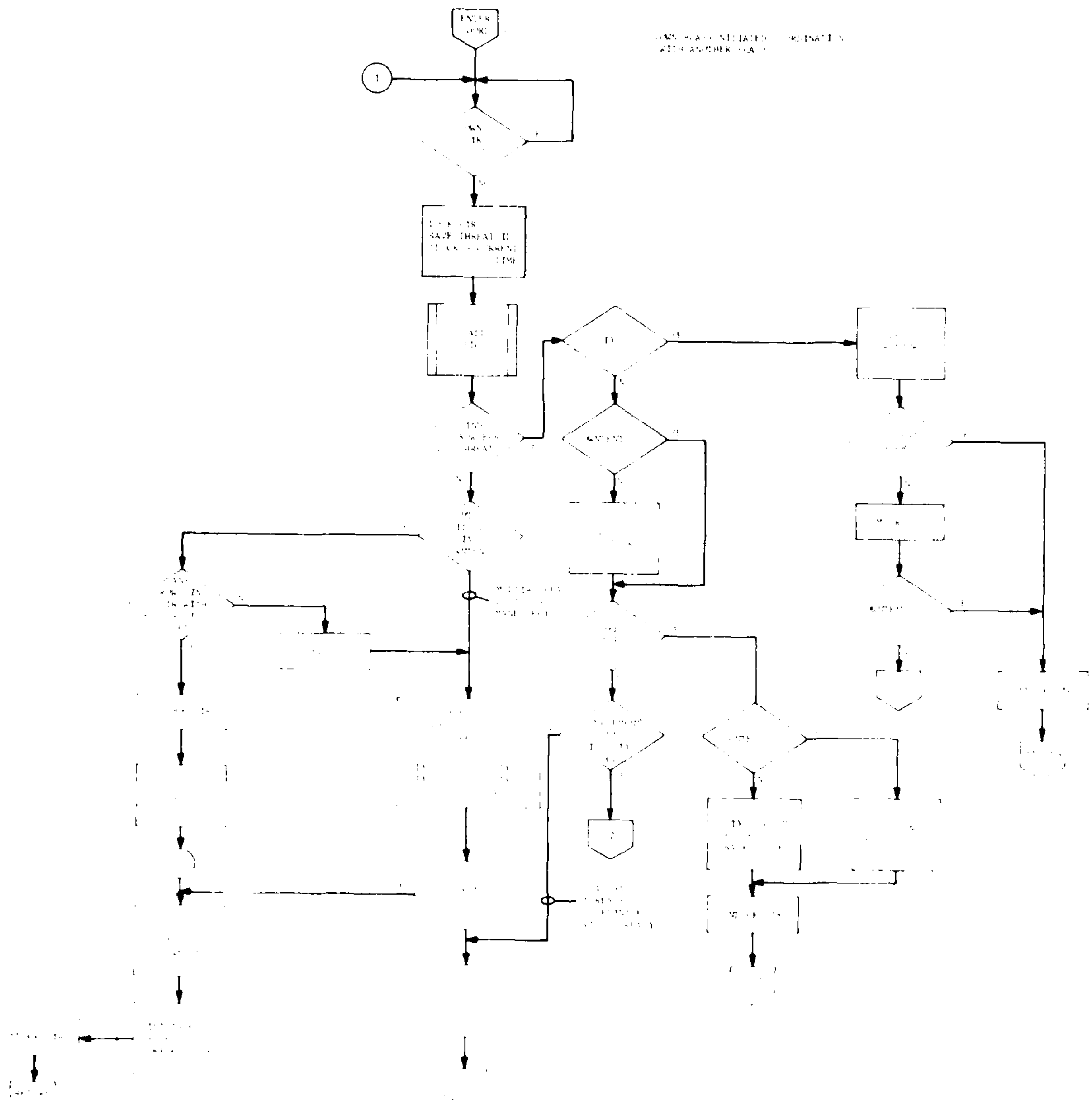


FIGURE 1. COORD LOGIC MODIFICATION - THREAT TRACK DATA BLOCK INITIALIZATION

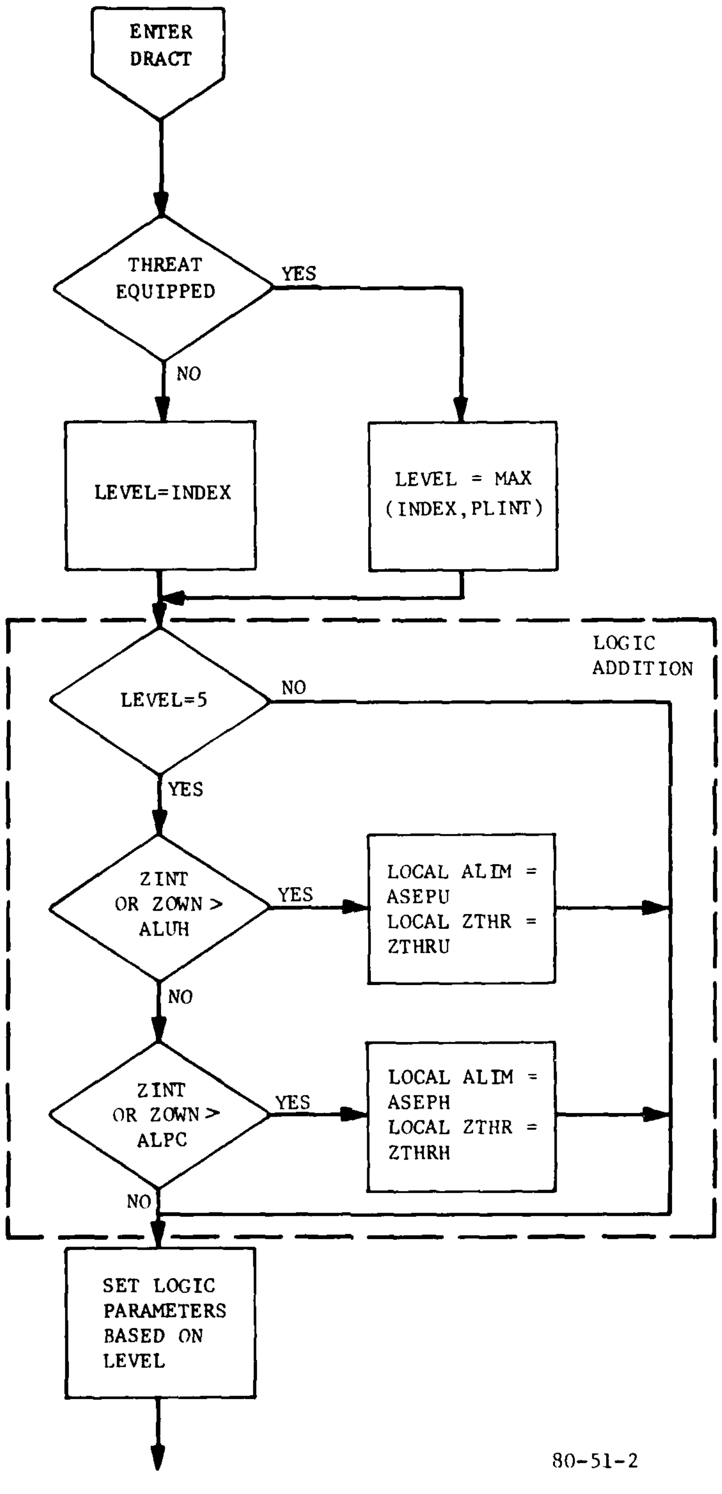


FIGURE 2. DRACT MODIFICATION - PROPER THREAT VOLUME SELECTION

unequipped intruder logic and a change in the β parameter for the vertical tracker. Tracker performance was reevaluated and the changes outlined by MITRE Corporation were incorporated. The modification resulted in an improvement in BCAS conflict resolution performance. The residual tracking errors that were of sufficient magnitudes to cause an incorrect sense choice did not cause a serious reduction in separation.

VERTICAL TRACKER PERFORMANCE (APRIL 79 LOGIC). The vertical tracker (described in reference 1) provides good vertical position information for threat detection; however, it provides poor vertical rate estimates. The vertical position and rate tracker error magnitudes and the sequential characteristics of the $\alpha - \beta$ tracker were obtained. Characteristics of the vertical tracker ($\alpha = 0.4$ and $\beta = 0.15$) are:

1. The $\alpha - \beta$ vertical tracker had been optimized for a 4.7-second update rate. Active BCAS update rate is 1 second.

2. Vertical position and rate tracker error magnitudes are dependent on the rate of mode C change. Tracker performance generally improves as the rate increases. Improvements also occur with a consistent pattern of mode C changes.

3. Projected vertical positions are based on the vertical rate estimates.

4. The vertical rate estimate oscillates around 0 feet per-second (ft/sec) after level-off.

Performance of the $\alpha - \beta$ vertical rate tracker used in TRIACT and TROACT was analyzed by inputting error-free mode C data. The pure mode C inputs represented reports from an aircraft established in a constant rate climb or descent. The data rate was one per second. The tracking procedure was initialized with the true altitude. Vertical position and vertical rate estimates were obtained once the tracker had stabilized.

Generally, the BCAS logic uses a 30- or 35-second projection of vertical position to determine sense of maneuver for unequipped intruders. The sequential error in vertical position projection at time t, E(t), was calculated as follows:

$$E(t)=(A(t)-B(t))+35*(\dot{A}(t)-\dot{B}(t))$$

where

$E(t)$ = error in the projected vertical position

$A(t)$ = true altitude at time t

$\dot{A}(t)$ = true vertical rate at time t

$B(t)$ = BCAS tracked altitude at time t

$\dot{B}(t)$ = BCAS tracked vertical rate at time t

For a contant vertical rate of -500 ft/min, the period of the error function is 12 seconds. The period P, in seconds, is calculated as follows:

$$P = 60*(100/Rate)$$

where the rate is in ft/min. The period of the error function represents the time between changes in the mode C reports for constant rate climbs or descents. The sequential errors in vertical position projection range from -421.7 to 485.6 feet. Fifty-eight percent of the time the error magnitude exceeds 300 feet.

For a constant rate of -1,000 ft/min, the period of the error function is reduced to 6 seconds. Errors as large as 539 ft/min are observed in the tracked rate. The magnitude of the projected altitude error exceeds 300 feet eighteen percent of the time. In general, rate tracker performance improves as the magnitude of the true rate increases; however, the consistency of the changes in the mode C altitude also affects the rate estimate. A vertical rate of -3,000 ft/min results in a consistent mode C altitude change every other second and a maximum projected altitude error of only 118 feet. The performance for a -3,900-ft/min rate decreases due to inconsistent changes in the mode C altitude. Although the magnitude of the rate has increased, the loss in consistency of the changes in the mode C altitude causes the maximal error in projected vertical position error to exceed 300 feet (almost 3 times the maximal error for a -3,000 ft/min rate). An ideal vertical tracker would provide for cases where the change in the mode C altitude is not consistent even though the vertical rate is constant.

Once the dynamic characteristics of the current tracked altitude and altitude rate were obtained, their impact on the resolution logic was analyzed. The major impact found was that sense determination logic for unequipped intruders used tracker vertical rate to determine the sense of maneuver. The errors in the vertical rate estimate can cause the incorrect sense to be chosen. The regions of incorrect sense choice and the loss in separation that result because of that incorrect choice have been identified.

The effect that the error in projected vertical position has on BCAS resolution performance was analyzed in two phases. First, the probability of an incorrect sense choice due to the vertical tracker errors was calculated. The probabilities were calculated for various combinations of true vertical rate and planned vertical miss distance. The vertical rates ranged from 500 to 2,000 ft/min. The planned vertical miss distance ranged from -600 to +600 feet. The probabilities were determined from the portion of time that the magnitude of the rate errors in the tracking cycle caused the projected vertical position error to be large enough to cause the wrong sense to be selected. The sense choice logic used was the logic found in reference 1 as shown in figure 2-3(d) of MTR 79W00110. The second phase of the analysis identified the impact of an incorrect sense choice on the resulting separation. For minimal planned vertical separation (200 feet), the probability of incorrect sense choice is quite high (0.50). However, when planned vertical separation at CPA is small, an incorrect sense choice does not reduce the resulting vertical separation at CPA. The largest impact caused by an incorrect sense choice occurs for higher values of planned vertical separation (400 to 600 feet).

In the first configuration analyzed, the BCAS aircraft was in level flight, and the intruder's vertical rate ranged from -2,000 to -500 ft/min and from 500 to 2,000 ft/min. A negative value of planned vertical miss distance implies the aircraft would be coaltitude before CPA occurred. The response to positive commands by the BCAS aircraft was identical to the modeled responses in the sense choice logic for unequipped intruders in reference 1. Figure 3 depicts the loss in separation that occurs with incorrect sense choice. The probability of wrong sense choice and the resulting loss in separation for this case is shown in table 2. The

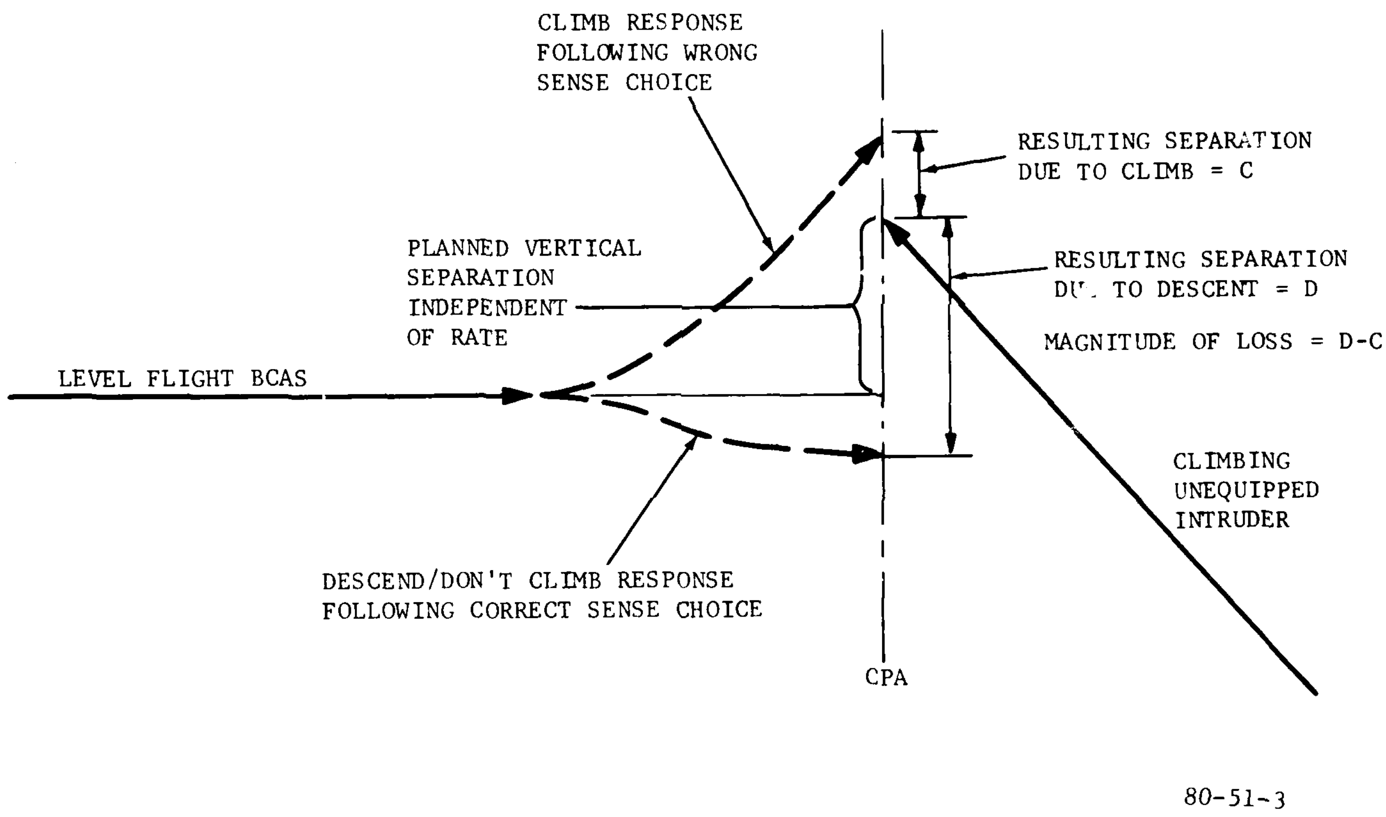


FIGURE 3. *MAGNITUDE OF SEPARATION LOSS DUE TO INCORRECT SENSE CHOICE*

TABLE 2. PROBABILITY AND MAGNITUDE OF LOSS IN SEPARATION DUE TO WRONG SENSE CHOICE (BCAS AIRCRAFT LEVEL — UNEQUIPPED INTRUDER CLIMBING/DESCENDING)

Intruder Vertical	Planned Vertical Separation (Magnitude of Loss)		
Rate (ft/min)	- 500 ft (325 ft)	- 400 ft (125 ft)	+ 300 ft (150 ft)
500	0.22	0.24	0.07
600	0.09	0.27	0.11
700	0	0.18	0.07
800	0	0.09	0.07
900	0	0.04	0.04
1,000	0	0	0.02
1,500	0	0	0
2,000	0	0	0
-500	0.16	0.31	0.16
-600	0.18	0.31	0.02
-700	0.04	0.16	0
-800	0.07	0.20	0
-900	0.09	0.11	0
1,000	0.02	0.18	0
1,500	0	0.02	0
1,700	0	0.18	0
2,000	0	0	0

NOTE: Vertical Rate Tracking Constant $\beta = 0.15$

magnitude of the loss in separation for a fixed value of planned vertical separation is shown in parentheses. Since the intruder is unequipped and the BCAS aircraft is initially in the level flight, the magnitude of loss is independent of the intruder's vertical rate.

The results in table 2 show that loss occurs with climb rates as high as 1,000 ft/min. For the lower climb rates and negative planned vertical separation, the probability of incorrect choice exceeds 0.20. Since the sense choice logic favored descent commands, the probability of incorrect sense choice extends over a wider range in the presence of a descending intruder. With -400 feet of planned vertical separation, an intruder descent rate as high as -1,700 ft/min results in a 0.18 probability of incorrect sense choice.

For the second configuration analyzed, the BCAS aircraft was climbing toward the level-flight unequipped intruder. A negative planned vertical miss distance implies that the BCAS aircraft would have climbed through the intruder's altitude and would have been above the intruder at CPA. The BCAS aircraft responded to commands as indicated in the response model in the unequipped intruder sense choice logic. Table 3 presents the results of the analysis.

Review of table 3 data shows that the impact of wrong choice in sense due to the tracker performance is restricted to low vertical rates (800 ft/min). In several cases, the probability of wrong sense choice is significant. With a planned vertical separation of -500 feet, and the equipped aircraft climbing at 500 ft/min, the wrong sense would be selected 25 percent of the time resulting in a loss of 325 feet in vertical separation. The response model in the unequipped intruder sense choice logic assumes that the commanded escape rate is obtained 8 seconds after command display regardless of the BCAS aircraft's vertical rate at time of command presentation. Therefore, the loss of vertical separation is independent of the BCAS aircraft's vertical rate.

In the last configuration analyzed, the BCAS aircraft was descending toward the level-flight unequipped intruder. The equipped aircraft response to commands was the same as that modeled in the unequipped intruder sense choice logic. The results presented in table 4 are almost identical to the results for the climbing, equipped aircraft.

Another problem with the vertical tracker is that after an aircraft levels off, the tracked vertical rate continues to oscillate around zero ft/min. The magnitude of the oscillations is dependent on the previous rate. Although the magnitude of the oscillations are continually decreasing, nonzero measurements of the vertical rate will continue. The oscillations frequently cause the selection of VSL alerts when, in fact, the own aircraft is in level flight.

The final problem with the vertical tracker is associated with high vertical rates (greater than 2,000 ft/min). Initially, the tracker performs quite well. The problem is that, once a BCAS aircraft responds to commands and reduces its vertical rate, the tracker overshoots the reduction which causes the algorithm to sense a miss (KHIT not updated). As a result, the commands are terminated early, only to reoccur once the tracker approximates the new rate.

Cases with wrong sense choice generally result in a reduction in resulting separation. The following discussion identifies the vertical rate regions in which this occurs. Tracker deficiencies on resolution logic are:

TABLE 3. PROBABILITY AND MAGNITUDE OF LOSS IN SEPARATION DUE TO WRONG SENSE CHOICE (BCAS AIRCRAFT CLIMBING — UNEQUIPPED INTRUDER LEVEL)

Equipped AC Rate (ft/min)	Planned Vertical Separation (Magnitude of Loss) - 500 ft (325 ft)	- 400 ft (125 ft)	+ 300 ft (150 ft)
500	0.25	0.31	0.18
600	0.11	0.23	0.09
700	0	0.22	0.09
800	0	0.13	0.04
900	0	0.07	0
1,000	0	0	0
1,500	0	0	0

NOTE: $\beta = 0.15$

TABLE 4. PROBABILITY AND MAGNITUDE OF LOSS IN SEPARATION DUE TO WRONG SENSE CHOICE (BCAS AIRCRAFT DESCENDING — UNEQUIPPED INTRUDER LEVEL)

Equipped AC Rate (ft min)	Planned Vertical Separation (Magnitude of Loss) - 400 ft (350 ft)	- 300 ft (500 ft)	+ 400 ft (125 ft)	+500 ft (325 ft)
-500	0.04	0.11	0.24	0.04
-600	0	0.09	0.20	0.06
-700	0	0	0.16	0.04
-800	0	0	0.18	0.06
-900	0	0	0.11	0.04
1,000	0	0	0.18	0
1,500	0	0	0	0
2,000	0	0	0	0

NOTE: $\beta = 0.15$

Cases with wrong sense choice generally result in a reduction in resulting separation. The following discussion identifies the vertical rate regions in which this occurs. Tracker deficiencies on resolution logic are:

1. Vertical position projections for unequipped intruders cause incorrect sense choices which reduces resulting separation.

2. Probability of wrong sense choice is high at low vertical rates.

3. Incorrect sense choice has largest impact on higher values of planned vertical separation (400 to 600 feet).

4. Oscillation in the rate estimate after level-off cause noneffective VSL alarms.

This analysis resulted in the recommendation that the performance of the vertical tracker be improved, especially at lower vertical rates. Parameter adjustment may improve tracker performance. If improvement does not occur, tradeoff in performance between the position tracker and rate tracker could also be analyzed. However, it may be necessary to develop a dynamic vertical rate tracker — one that would vary the tracking parameters based on the mode C altitude change history. In fact, a very simple improvement in sense choice logic might be to use the mode C altitude change rate to approximate the vertical rate. This rate would be based on more than a single second of data.

<u>IMPROVED VERTICAL TRACKER PERFORMANCE (AUGUST 1979 MODIFICATION)</u>. In MITRE letter W46-0532 dated August 10, 1979 (reference 7), MITRE Corporation modified the unequipped intruder sense choice logic and reduced the β parameter from 0.15 to 0.10 to tighten the tracker and reduce tracker noise-induced problems. The vertical tracker was reevaluated with the new logic and β parameter. The $\alpha-\beta$ vertical tracker performance was again characterized in terms of the vertical position and rate tracker error magnitudes. The procedure that was used in the previous evaluation was repeated. The new tracker parameters are: $\alpha=0.4$; $\beta=0.10$. Table 5 depicts tracker performance for constant vertical rates of -500 and -1,000 ft/min for both β parameter values. For a β value of 0.15, the sequential errors in vertical position projection ranged from -422 to 486 feet with the error magnitude greater than 300 feet 58 percent of the time. A significant improvement is observed when the new value of $\beta = 0.10$ is used. The sequential errors in vertical position projection varied from -330 to 280 feet with the error magnitude greater than 300 feet only 8 percent of the time. For a constant vertical rate of -1,000 ft/min and a β value of 0.15, the sequential errors in the position projection range from -345 to 203 feet with the error magnitude greater than 300 feet 17 percent of the time. For a β value of 0.10, the sequential errors in the position projection ranged from -233 to 107 feet. The error magnitude never exceeded 300 feet and only exceeded 110 feet 17 percent of the time.

Table 6 compares the tracker performance for vertical rates of -3,000 and -3,900 ft/min. As in the previous analysis, tracker performance <u>generally</u> improves as the magnitude of the true rate increases. However, inconsistency in the change rate of the reported mode C altitude decreases tracker performance. At a rate of -3,000 ft/min, the mode C altitude changes every 2 seconds. At a rate of -3,900 ft/min, the mode C altitude changes in an inconsistent pattern averaging 1.54 seconds between changes. The new β value cannot eliminate this phenomenon; however, the maximal error has been reduced. For a rate of -3,000 ft/min, the previous maximum projected error of 118 feet is reduced to 87 feet. For a rate of -3,900 ft/min, the maximum projected error of 326 feet is reduced to 204 feet.

TABLE 5. COMPARISON OF TRACKER ERRORS (LOW DESCENT RATE)

	-500 feet/minute				-1,000 feet/minute			
	BETAZ = 0.10 (New)		BETAZ = 0.15 (Old)		BETAZ = 0.10 (New)		BETAZ = 0.15 (Old)	
Cycle	Rate Error feet/sec	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)
25	-0.25	-1.70	-2.75	-86.92	0.62	19.09	0.79	26.58
26	-2.59	-93.27	-6.23	-220.68	-2.50	-101.92	-4.14	-158.37
27	-4.57	-173.05	-8.63	-317.41	-5.78	-232.66	-8.98	-344.74
28	-6.13	-238.61	-10.03	-378.68	1.15	32.18	1.94	58.49
29	-7.29	-289.93	-10.61	-410.73	3.54	126.21	5.74	202.51
30	-8.09	-328.39	-10.62	-421.67	2.94	106.68	4.64	166.89
31	1.40	33.88	4.72	145.43	0.63	19.30	0.79	26.33
32	6.13	219.53	11.96	423.04	-2.49	-101.71	-4.15	-158.60
33	7.52	279.80	13.26	484.09	-5.78	-232.48	-8.98	-344.93
34	6.76	258.00	10.81	404.77	1.16	32.30	1.96	58.43
35	4.80	188.27	6.46	251.88	3.54	126.29	5.74	202.39

TABLE 6. COMPARISON OF TRACKER ERRORS (HIGH DESCENT RATE)

	-3,000 feet/minute				-3,9000 feet/minute			
	BETAZ = 0.10 (New)		BETAZ = 0.15 (Old)		BETAZ = 0.10 (New)		BETAZ = 0.15 (Old)	
Cycle	Rate Error feet/sec	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)	Rate Error (feet/sec)	Projected Position Error (feet)
25	1.61	86.81	2.46	116.26	0.08	4.78	-0.61	-17.17
26	-1.61	-37.26	-2.47	-66.79	-0.85	34.96	0.37	18.84
27	1.61	86.98	2.45	115.85	4.73	187.04	6.14	236.82
28	-1.61	-37.21	-2.47	66.98	0.08	10.56	-1.06	-28.45
29	1.61	86.97	2.45	115.81	0.78	38.06	0.02	11.36
30	-1.61	-37.25	-2.47	-66.94	4.63	188.72	5.92	233.50
31	1.61	86.89	2.45	115.90	0.03	11.71	-1.18	-28.05
32	-1.61	-37.34	-2.47	-66.84	0.68	39.30	-0.02	14.67
33	1.61	86.89	2.45	115.99	-5.47	-199.61	-9.06	-326.20
34	-1.62	-37.41	-2.47	-66.77	-5.11	-191.04	-7.89	-290.85
35	1.61	86.75	2.45	116.03	-0.88	-31.34	-0.75	-29.83

The impact of the new tracking parameter on conflict resolution performance was reevaluated using the new unequipped intruder logic defined in reference 7. Results are compared to the results obtained with the previous unequipped intruder logic (reference 1) and β value of 0.15. The probability of an incorrect sense choice due to vertical tracker errors was calculated for various combinations of true vertical rate and planned vertical miss distance. The intruder vertical rates ranged from 500 to 2,000 ft/min. The planned vertical miss distance ranged from -800 to +800 feet. The probabilities were obtained by determining the percentage of time the projected vertical position error was large enough to cause the wrong sense to be selected. Since the unequipped sense choice logic was modified by reference 7 to include an acceleration model of the own aircraft's delay in achieving the desired escape rate, a direct comparison for β=0.1 versus β=0.15 is only available when the BCAS aircraft is level. This comparison is summarized in table 7. A review of table 7 shows that the probability of incorrect sense choice has been significantly reduced, but not eliminated. The probability of incorrect sense choice is 0.27 when the intruder is climbing at 500 ft/min and the BCAS aircraft is 300 feet above the threat at CPA. The high incidence of incorrect sense choice occurs because the sense choice logic assumes a minimum 1,500-ft/min descent escape rate, but only a 1,000-ft/min climb escape rate by the level-flight BCAS aircraft.

UNEQUIPPED INTRUDER SENSE CHOICE LOGIC PERFORMANCE.

The original sense choice logic for unequipped intruders models both a BCAS climb response and a BCAS descent response. The sense of maneuver selected is that maneuver which provides the larger separation. Although the concept of modeling both a climb and descent maneuver seems promising, the unequipped intruder sense choice logic (reference 1) contains several flaws which result in poor or marginal separation performance. Each of the problem areas is discussed in detail. Examples are included to show the impact of the deficiencies in the sense choice logic. Logic improvements provided to SRDS and MITRE to address specific problem areas are reviewed.

The mathematical terms used in the discussion of the unequipped intruder sense choice logic deficiencies conform to the variable names used in list of BCAS algorithm terms.

LACK OF ACCELERATION DELAY IN THE SENSE CHOICE MODEL. A difficulty arises in the selection of sense for unequipped intruders when the own aircraft's vertical rate is high, the intruder's vertical rate is near zero, and the planned vertical separation is large in the negative sense (|planned vertical separation|>750 feet). As before, negative values of planned vertical miss distance imply the vertical tracks cross prior to CPA.

Figure 4 presents an encounter geometry that causes the original BCAS logic to select the sense of maneuver which results in marginal performance. The BCAS aircraft is initially above the unequipped level-flight intruder. Without BCAS interaction, the BCAS aircraft would pass 1,300 feet below the intruder at CPA. The proper sense choice is "descend"; however, the original BCAS logic causes a "climb" command to be issued resulting in a loss of existing separation.

The example geometry causes the sense of maneuver to be selected 37 seconds prior to CPA. At this time ZINT-ZOWN = 1,171.63 feet. The original sense choice logic presumes that the current tracked BCAS aircraft's vertical rate, ZDOWN, continues for an additional 8 seconds. At this time the vertical escape rate (16.67 ft/sec

TABLE 7. PROBABILITY OF AN INCORRECT SENSE CHOICE AND MAGNITUDE OF LOSS IN SEPARATION

BCAS Aircraft Level

Intruder	Planned Vertical Separation at CPA (Magnitude of Loss)					
	-500 ft (325 ft)		-400 ft (125 ft)		+ 300 ft (150ft)	
Rate (ft/min)	β = 0.15	β = 0.10	β = 0.15	β = 0.10	β = 0.15	β = 0.10
500	0.22	0.00	0.24	0.00	0.07	0.27
600	0.09	0.00	0.27	0.00	0.11	0.18
700	0.00	0.00	0.18	0.00	0.07	0.09
800	0.00	0.00	0.09	0.00	0.07	0.04
900	0.00	0.00	0.04	0.00	0.04	0.04
1,000	0.00	0.00	0.00	0.00	0.02	0.00
1,500	0.00	0.00	0.00	0.00	0.00	0.00
2,000	0.00	0.00	0.00	0.00	0.00	0.00
-500	0.16	0.00	0.31	0.07	0.16	0.00
-600	0.18	0.00	0.31	0.09	0.02	0.00
-700	0.04	0.00	0.16	0.04	0.00	0.00
-800	0.07	0.00	0.20	0.07	0.00	0.00
-900	0.09	0.00	0.11	0.00	0.00	0.00
-1,000	0.02	0.00	0.18	0.00	0.00	0.00
-1,500	0.00	0.00	0.02	0.00	0.00	0.00
-1,700	0.00	0.00	0.18	0.18	0.00	0.00
-2,000	0.00	0.00	0.00	0.18	0.00	0.00

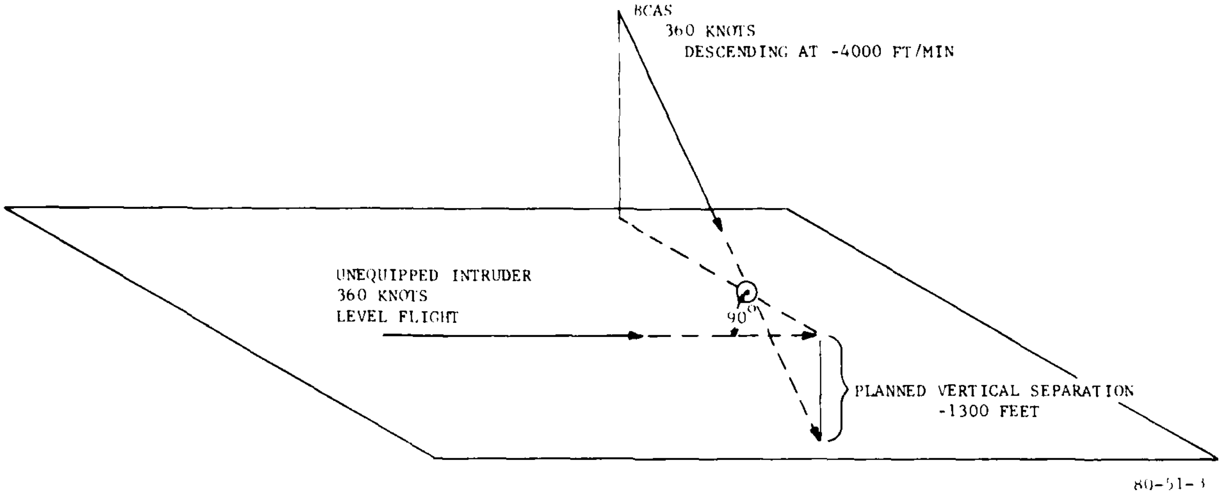


FIGURE 4. ENCOUNTER WHICH EXHIBITS POOR BCAS PERFORMANCE DUE TO LACK OF ACCELERATION MODELING

for climbs or -25 ft/sec for descents) is assumed to have been achieved. The time delay to achieve the escape rate in response to commands is fixed at 8 seconds. The time delay is not dependent on the amount of change in rate that is required to achieve the modeled response. In the example cited, the descent rate is -66.67 ft/sec (a nominal rate for high performance aircraft). The sense choice logic assumes that a 16.67-ft/sec climb can be established in 8 seconds. A nominal 5-second pilot response delay requires that the average acceleration rate exceeds 0.8 g to achieve the modeled response.

When command sense selection occurs, the BCAS variable values which result in the climb choice are:

ZDOWN = -63.92 feet/second (tracking error of 2.75 feet/seconds)

ZDINT = 0 feet/second

TRTRU = 37.36 seconds

TVPESC = 35 seconds

TV1 = 8 seconds

TESC = 35-8 = 27 seconds

The modeled climb separation using these values is:

ZMPCLM = ZINT - ZOWN - TV1*ZDOWN - TESC*ZDCLM

= -1,171.63 - 8*(-63.92) - 27*(16.67)

$= -1{,}110.36$ feet.

Similarly the modeled descent separation is:

$$ZMPDES = ZINT - ZOWN - TV1*ZDOWN - TESC*ZDDES$$

$$= -1{,}171.63 - 8*(-63.92) - 27(-63.92)$$

$$= 1{,}065.57 \text{ feet.}$$

Because $|ZMPCLM| > |ZMPDES|$ the climb sense was selected.

To address the problem of a fixed response delay independent of the magnitude of the response, MITRE Corporation developed a new unequipped intruder sense choice logic which includes an acceleration model. The logic modification is shown in figure 5. For the example shown in figure 4, the new logic will result in the following calculations:

ZDCLM = 16.67 feet per second

ZDDES = -63.92 feet per second

TDC = Time to establish climb escape rate = 8+(16.67+63.92)/8
= 18.07 seconds

TDD = Time to establish descent escape rate = 8+(63.92-63.92)/8
= 8 seconds

TSSC = Time of maneuvering at climb escape rate = TRTRU-TDC
= 19.29 seconds

TSSD = Time of maneuvering at descent escape rate = TRTRU-TDD
= 29.36 seconds

Using these new values and the new model which includes acceleration delays, the model climb separation becomes:

$$ZMPCLM = ZINT - ZOWN - TDC*ZDOWN - TSSC*ZDCLM - 4*(TDC - TV1)^2$$

$$= -1{,}171.63 - 18.07\,(-63.92) - 19.29(16.67) - 4(10.07)^2$$

$$= -743.78 \text{ feet}$$

The modeled descent separation becomes:

$$ZMPDES = ZINT - ZOWN - TDD*ZDOWN - TSSD*ZDDES + 4*(TDD - 8)^2$$

$$ZMPDES = -1{,}171.63 - 8*(-63.92) + (-29.36)*(-63.92)+4(0)^2$$
$$= 1{,}216.42 \text{ feet}$$

Since $|ZMPDES| > |ZMPCLM|$, the proper descent sense is selected.

<u>PROJECTIONS OF VERTICAL POSITION WHEN TESC IS NEGATIVE</u>. TESC is the anticipated time of maneuver prior to CPA. The original unequipped intruder sense choice logic

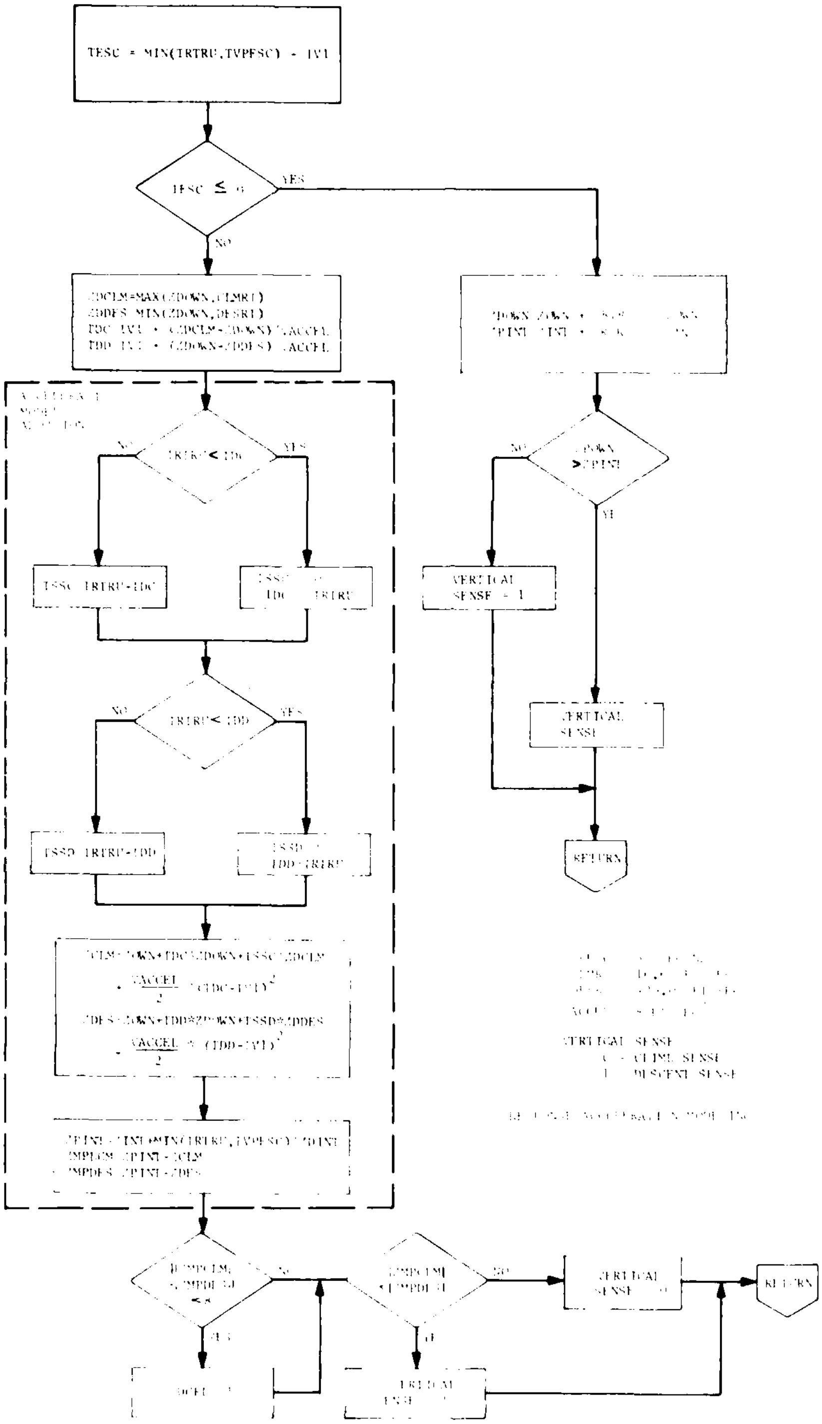


FIGURE 5. MODIFIED UNEQUIPPED INTRUDER SENSE CHOICE LOGIC

does not consider the impact of negative values of TESC. An intruder may not be initially declared a threat until it is within 5 seconds of minimum range; i.e., -R/RD is less than 5 seconds.

TESC is calculated as follows:

$$TESC = MIN\ (TRTRU,\ TVPESC)\ \ -\ TV1$$

where:

$$TRTRU = -R/RD < 5 \text{ seconds}$$

$$TVPESC = 25 \text{ seconds}$$

and the response delay parameter TV1 = 5 seconds

As a result TESC = TRTRU - 5 seconds, which is negative.

This discrepancy leads to the wrong choice of command sense. Initially, it was thought that TESC<0 could only occur for late intruder track initiation caused by popup threats, own aircraft exiting performance level 2 areas, or by high horizontal accelerations by both aircraft. Further analysis, however, has identified a wide range of highly likely encounter geometries in which intruder track initiation occurs quite early but still results in negative values of TESC and incorrect sense choice.

Sense choice logic is only exercised when KHIT is first updated, that is, when the first hit is declared. An intruder can penetrate threat volume (TAUR<25), but unless VMD <750 feet, a miss is declared and sense selection is delayed. The likely geometries which result in negative values of TESC include own aircraft level and intruder descending from above so as to pass above own aircraft with the planned vertical miss distance near ZTHR (750 feet). Figure 6 presents an example of such an encounter.

Initially, the intruder penetrates the threat volume (TAUR<25) 11 seconds prior to CPA. However, since VMD remains greater than 750 feet, threat declaration does not occur until 2 seconds prior to CPA. At this time, command sense is determined. By now TRTRU = 0.19/0.04 = 4.75 resulting in TESC = 4.75 - 8 = -3.25 seconds. On this logic cycle, ZDINT = -70.99 feet/second and ZDOWN = 0 feet/second, ZOWN = 9,200 feet and ZINT = 10,223 feet. This causes the modeled climb separation to be calculated as follows:

$$\begin{aligned} ZMPCLM &= 1{,}023.73 \text{ feet} + TRTRU*ZDINT - TV1*ZDOWN - TESC*CLMRT \\ &= 1{,}023.73 \text{ feet} + 4.75*(-70.99) - 8(0) - (-3.25)(16.67) \\ &= 740.7 \text{ feet} \end{aligned}$$

The modeled descent separation is calculated as:

$$\begin{aligned} ZMPDES &= 1{,}023.73 + TRTRU*ZDINT - TV1*ZDOWN - TESC*DESRT \\ &= 1{,}023.73 + 4.75*(-70.99) - 8(0) - (-3.25)(-25) \\ &= 605.3 \text{ feet} \end{aligned}$$

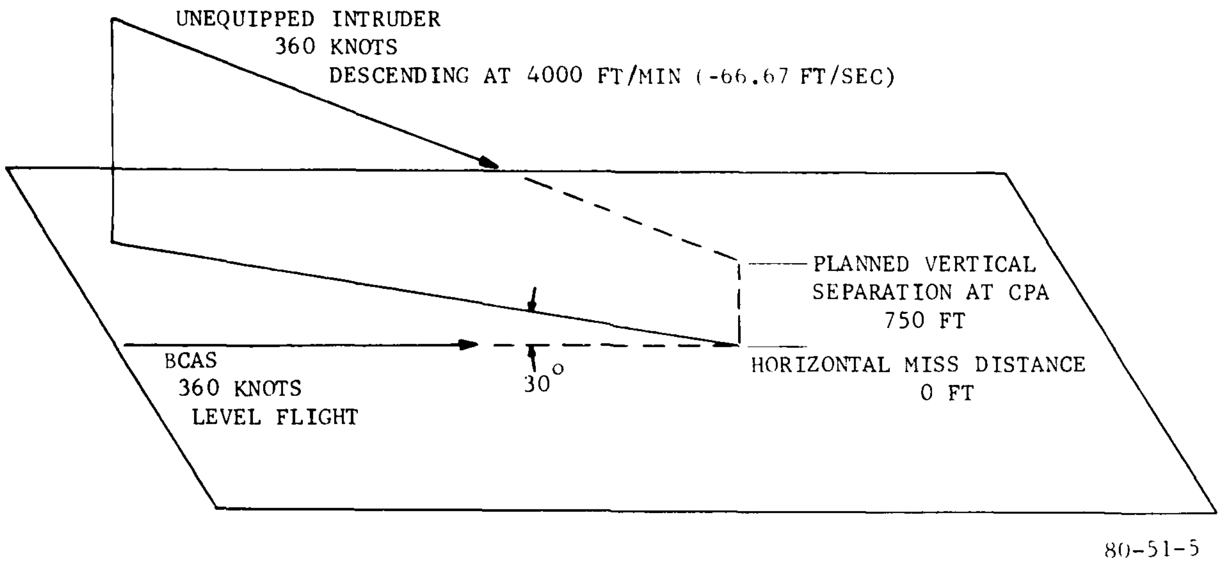


FIGURE 6. ENCOUNTER WHICH RESULTS IN NEGATIVE VALUE OF TESC

Since |ZMPCLM| > |ZMPDES|, the sense for own aircraft is set for a climb (don't descend) even though the intruder will remain above. The next logic cycle, VMD > 750 feet and KHIT is not updated. On the following cycle, 470 feet < VMD < 750 feet causes the incorrect negative command, don't descend, to be selected.

The ability to establish a response to a BCAS command with less than 8 seconds to minimum range is questionable. As a result, no response should be modeled by the logic. Sense choice should be based on the projected vertical miss distance using the current own and intruder vertical rates. The logic shown in figure 7 has been added to prevent incorrect sense choice when TESC $\leq$ 0. This logic (shown in figure 7) assumes that no response occurs because the aircraft are 8 seconds or less from the closest point of approach. As a result, sense choice is based strictly on projected vertical position in TRTRU seconds.

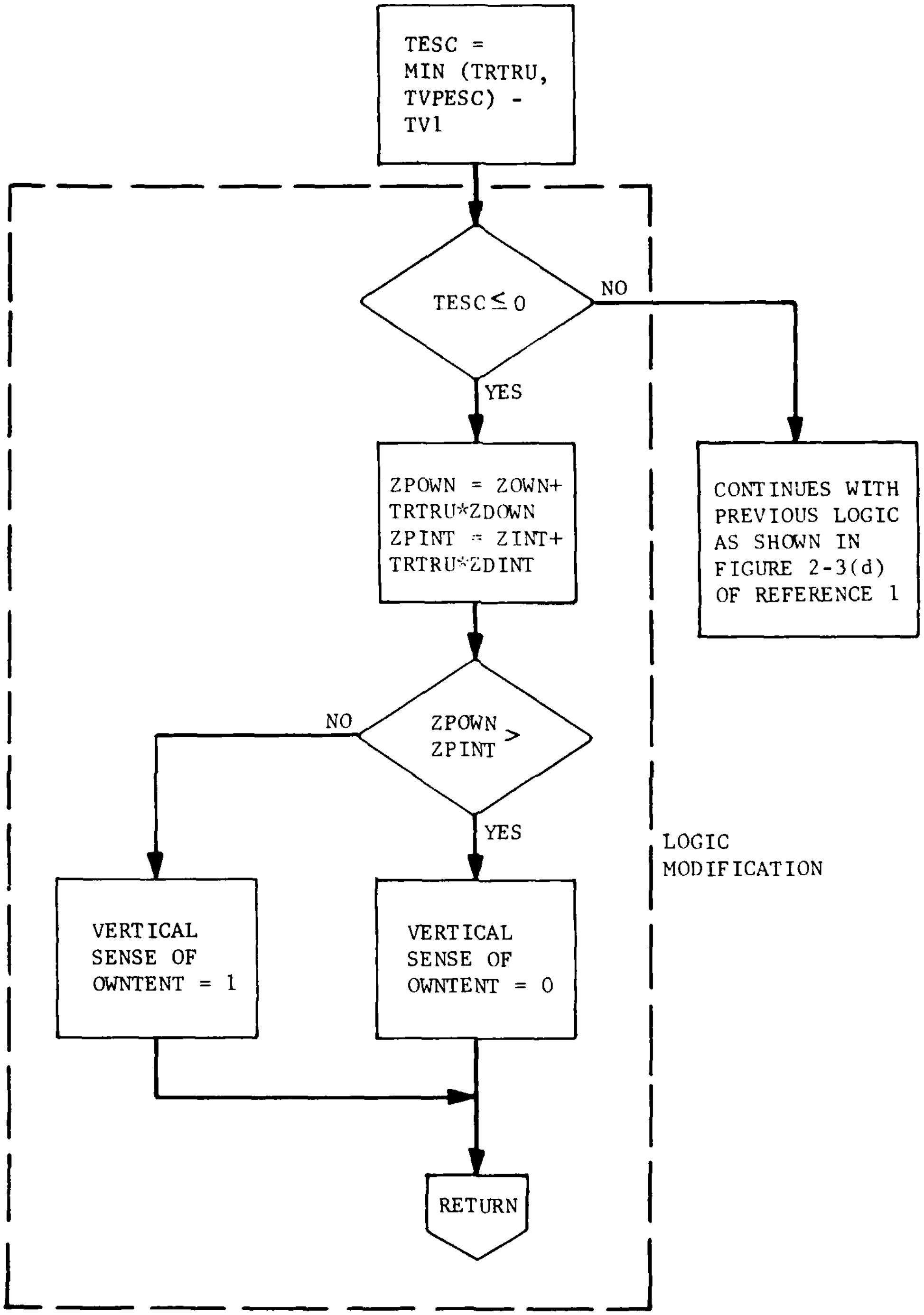
Sense selection based on this method results in an increase in the vertical miss distance if the BCAS aircraft responds to the command. When the new logic change shown in figure 7 is used to determine sense for the example cited in figure 6, then:

$$\text{ZPOWN} = 9{,}200 \text{ feet} + 4.75(0) = 9{,}200 \text{ feet}$$

$$\text{ZPINT} = 10{,}223 \text{ feet} + 4.75(-70.99 \text{ feet}) = 9{,}885.8 \text{ feet}$$

and since ZPOWN < ZPINT, the correct descent (no climb) sense is selected.

<u>CONSERVATIVE PROJECTIONS (UNDERESTIMATION) OF VERTICAL MISS DISTANCE</u>. A characteristic of good BCAS performance is the detection of conditions which require



VARIABLE ADDED:

ZPOWN = PREDICTED OWN ALTITUDE WHEN TRTRU $\leq$ 8 SECONDS.

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FIGURE 7. DRACT MODIFICATION - NEGATIVE TESC VALUES

no BCAS action because of large vertical separation although a high vertical closure rate exists. When BCAS does generate alerts in these cases, the alerts certainly should not reduce separation. The method of projecting vertical rates to obtain VMD utilizes a conservative time estimate for the projection. While this method may be desired for unequipped intruder position projections, it presents problems for high vertical rates for own aircraft when the intruder is level and a large planned negative vertical miss distance exists.

Negative vertical miss distances occur when vertical track crossings take place prior to CPA. In the presence of high rates, large negative vertical miss distances can exist. The algorithm must be able to identify this condition and not issue an unnecessary alarm which reduces separation. This is especially true when the vertical closure is due to own aircraft. Figure 8 presents an example of a case where BCAS interaction causes the BCAS aircraft to climb which reduces the vertical separation from 1,900 feet to less than 800 feet. BCAS detects the intruder and provides resolution 48 seconds prior to CPA. At that time, the calculated values of the BCAS variables necessary to determine the projected vertical miss distance, VMD, are:

A = 1,304.62 feet

TAUV = 20.05 seconds

ADOT = A/TAUV = -65.07 feet/second

TRTRU = -R/RD = 2.49/0.05 = 49.8 seconds

TVPCMD = 25 seconds

so that:

VMD = A + ADOT*MIN(TVPCMD,TRTRU)

= 1,304.62 - 25*(65.07) = 322.13 feet

VMD underestimates the true vertical miss distance (1,900 feet) by more than 1,500 feet.

The vertical miss distance estimate is conservative because the low crossing angle causes a large difference between TVPCMD and TRTRU when the threat is initially detected and BCAS resolution is requested. Although 49.8 seconds remain until CPA, the algorithm only projects the vertical rate for 25 seconds, the original logic value of TVPCMD.

Since the resulting value of |VMD| is less than the threshold for positive BCAS commands (ALIM = 470 feet), a positive climb command is generated when no command is required.

To reduce the impact of conservative projections (underestimates) of the vertical miss distance when vertical track crossing occurs prior to CPA, MITRE Corporation has made two revisions to the logic. The first revision increases the value of TVPCMD (the look-ahead time for altitude detection) by 10 seconds. For the example encounter shown in figure 8, the new value of VMD is -972.83 feet. Since this is greater than the threshold for threat detection (750 feet), no command results.

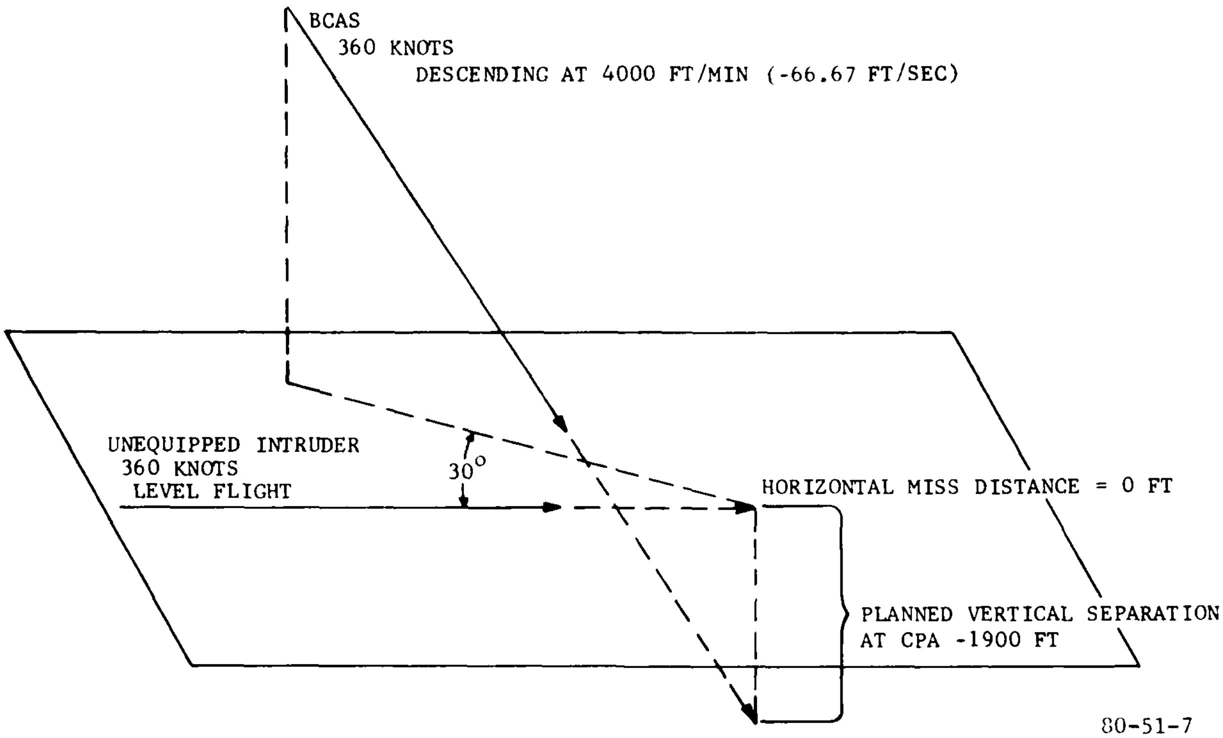

FIGURE 8. ENCOUNTER WHICH RESULTS IN CONSERVATIVE VERTICAL MISS DISTANCE PROJECTION

A second, more sophisticated revision by MITRE compares the projected range at the time of the predicted coaltitude condition with range tau distance modifying value DMOD. The equation which calculates the projected range at coaltitude is

$$\text{Range Projection} = |R + RD * TAUV|$$

For the example encounter, range projection = 1.4875 nautical miles (nmi).

Since the projected range is greater then DMOD (1 nmi), a command is not required. Figure 9 pictorially depicts this method of filtering threats based on projected range.

INCORRECT UNEQUIPPED INTRUDER SENSE CHOICE DURING NEAR LEVEL-FLIGHT TAIL CHASE ENCOUNTERS. In reviewing FTEG results, it is apparent that when the relative vertical closure rate (ADOT) between a BCAS aircraft and unequipped intruder is low, the current relative vertical position should be used to select the sense of the escape maneuver. This is not done in the original logic (reference 1). A problem exists for the cases in which the BCAS aircraft is above the intruder. The problem is most pronounced in tail chase encounters. These encounters are characterized by high true tau values (TRTRU = -R/RD) initially in the encounter when sense of maneuver is selected.

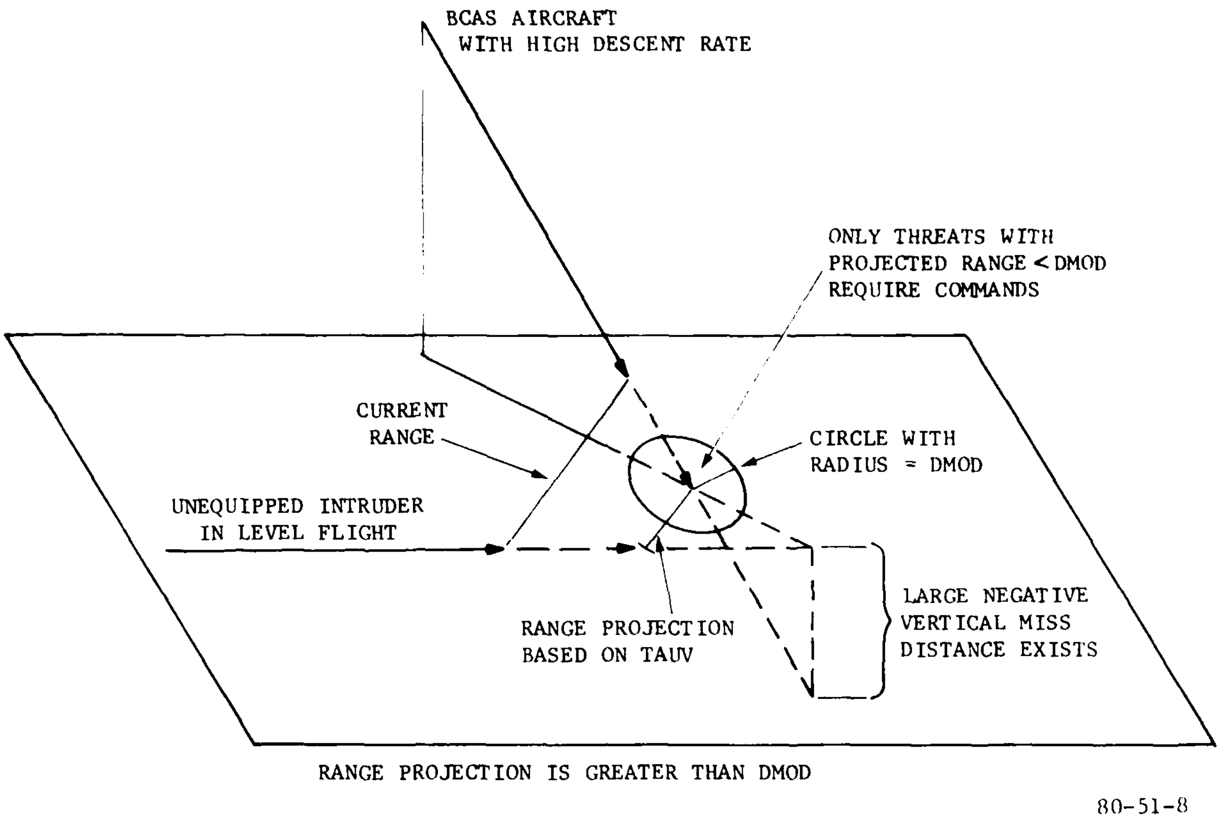

FIGURE 9. ENCOUNTER THAT WOULD HAVE THE ALARM FILTERED BY RANGE PROJECTION

The BCAS logic selects sense of maneuver for unequipped intruders by modeling both a climb escape maneuver and a descent escape maneuver using TRTRU. The logic selects the maneuver which generates the greater separation at the projected CPA. The logic assumes a descent escape rate of -1,500 ft/min and a climb escape rate of 1,000 ft/min. For most conditions, this realistically portrays the approximate magnitudes of pilot response actions and results in the proper maneuver sense choice. However, for near level-flight tail chase encounters where TRTRU is large, the larger magnitude of the descent escape rate (1,500 versus 1,000 ft/min), projected over large TRTRU, can offset the BCAS aircraft's altitude above the intruder. This results in an improper descend command.

The encounter conditions which led to an incorrect sense choice are shown in figure 10. The sequential relative vertical positions following the generation of the incorrect BCAS descend command are shown in figure 11. Although the range when the coaltitude condition occurs is 0.48 nmi, a climb command would have been more appropriate.

Two modifications to the sense choice logic were evaluated. The first modification, provided by MITRE, limits the length of time of the modeled escape response to a maximum of 35 seconds (instead of TRTRU seconds). For tail chase encounters,

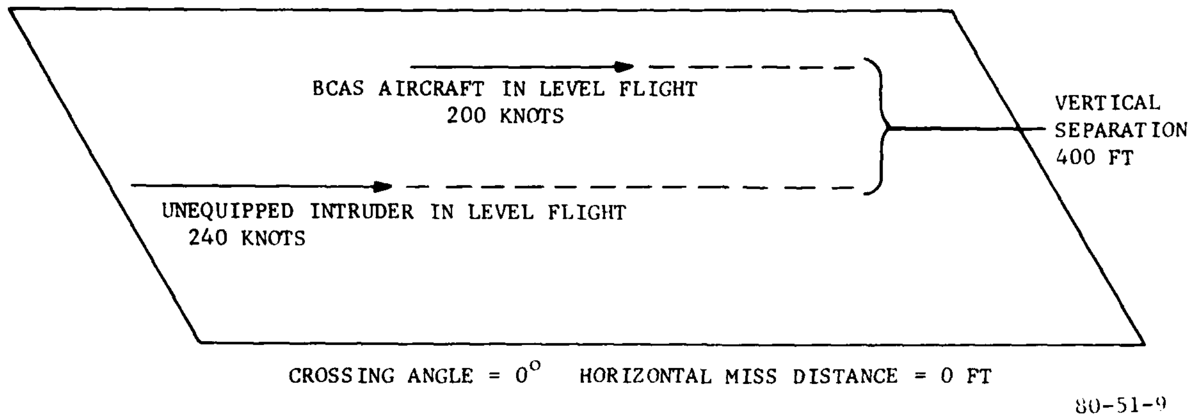

FIGURE 10. TAIL CHASE ENCOUNTER CAUSING INCORRECT SENSE CHOICE IN THE CASE OF UNEQUIPPED INTRUDERS

the length of escape response is reduced significantly. This reduction prevents the larger magnitude of the modeled descent escape rate from offsetting the BCAS aircraft's altitude separation above the intruder. The second modification, suggested by Computer Science Corporation (CSC), checks the vertical rate of both the intruder and the BCAS aircraft. When the magnitude of each rate is less than 5 ft/sec (300 ft/min), the maneuver sense choice is based on the current relative vertical position (i.e., the BCAS aircraft will climb when above and descend when below). Either one of the two logic modifications will prevent the generation of a descent command for the encounter shown in figure 10. Both modifications have been added to the BCAS logic.

VERTICAL ACCELERATION PERFORMANCE.

An evaluation was made of the BCAS algorithm's ability (1) to detect a change in an unequipped intruder's vertical rate and (2) to issue a command in time to ensure separation. The new unequipped intruder sense choice logic and a β parameter value of 0.10 (reference 7) were used to evaluate vertical acceleration performance.

The basic geometry used to evaluate the vertical acceleration detection and resolution logic is shown in figure 12. An unequipped intruder is initially descending at -4,000 ft/min. The BCAS aircraft is in level flight. The intruder aircraft levels off above the BCAS aircraft on a reciprocal heading. Neither aircraft maneuvers horizontally. The duration of the intruder's level-flight segment prior to CPA varied from 60 to 5 seconds. Throughout the analysis, the vertical acceleration rate was 0.5 g for both aircraft. The pilot response delay was fixed at 5 seconds.

The performance results are illustrated in figure 13. Figure 13 shows that when the planned level-flight time is less than 15 seconds, the algorithm issues a climb command prior to the intruder leveling off. With 15 to 30 seconds of planned level flight, a climb command is issued 2 to 4 seconds after the intruder levels off.

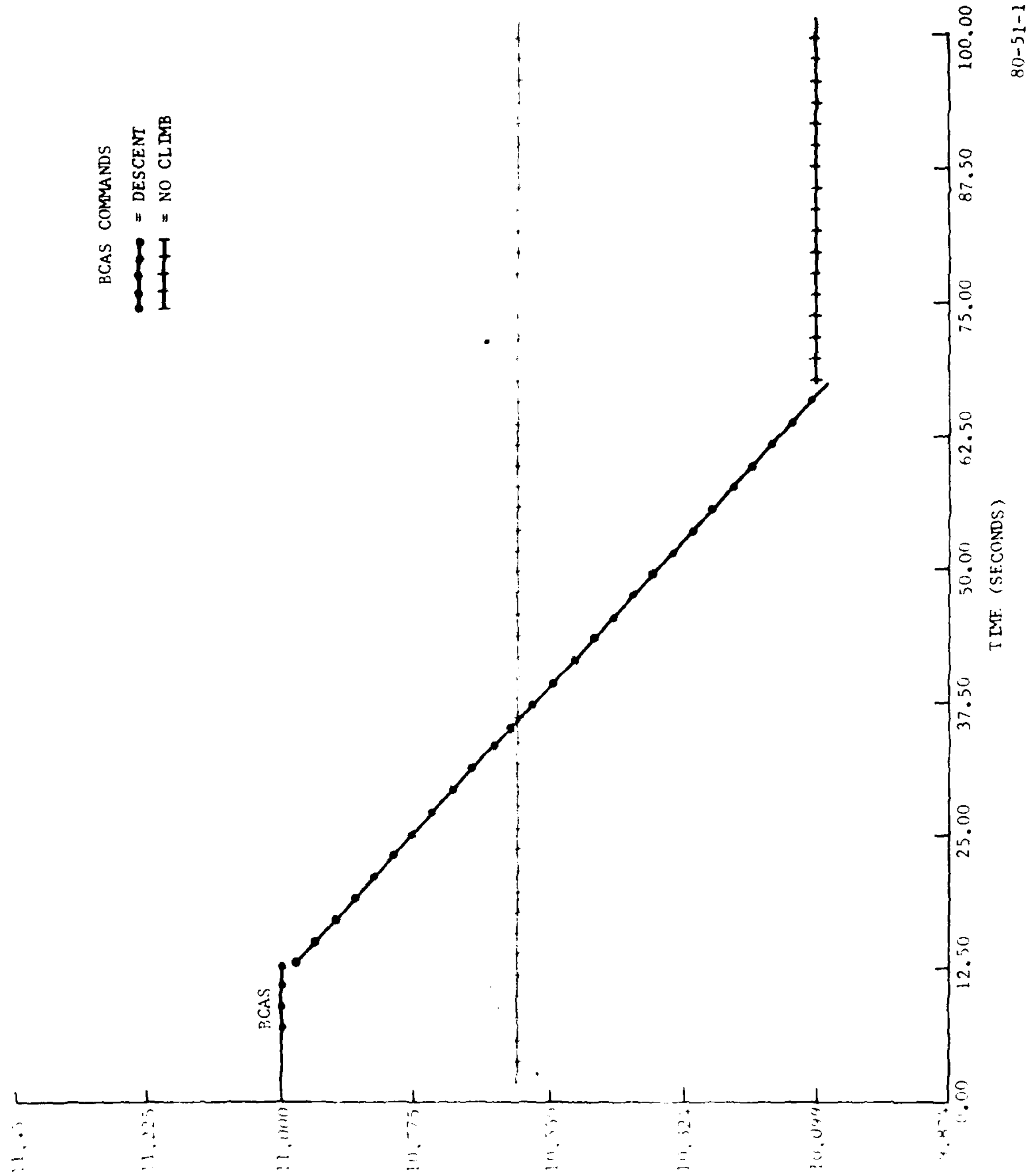

FIGURE 11. ALTITUDE VERSUS TIME PLOT FOR TAIL CHASE ENCOUNTER

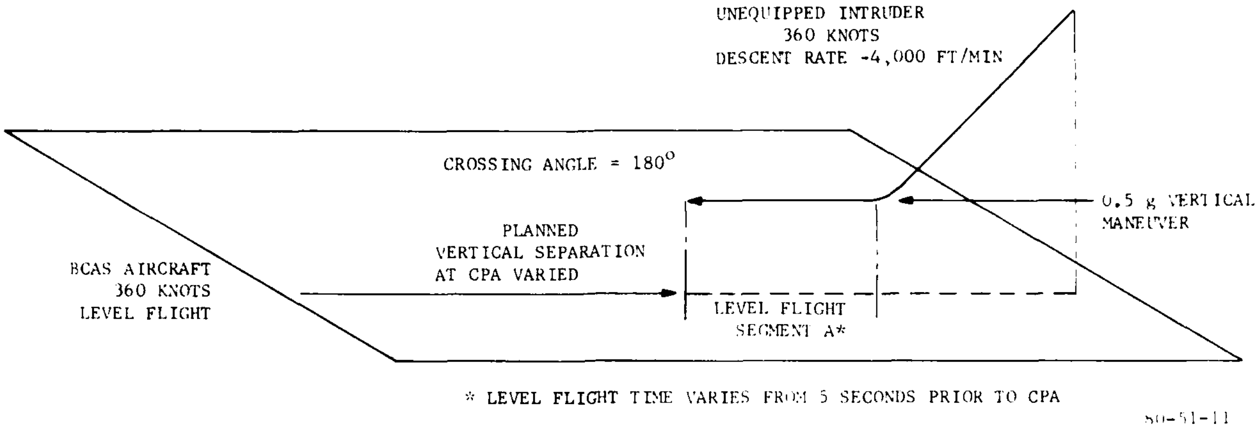

FIGURE 12. GEOMETRY FOR UNEQUIPPED INTRUDER VERTICAL ACCELERATION EVALUATION

When the duration of the intruder level-flight segment exceeds 35 seconds, a descend command is issued 26 seconds prior to planned CPA time.

The climb command issued after the intruder levels off is due to vertical tracker lag and the high vertical deceleration by the intruder. The BCAS vertical rate tracker continues to project a descent for the intruder for several seconds after the intruder levels off. Since the intruder is projected to be below the BCAS aircraft, the BCAS aircraft receives a climb command. If the true vertical rate (indicating level flight) had been available, the BCAS aircraft would have received a descend command.

Figure 14 depicts the observed separation following the BCAS commands when the intruder levels off at 100, 300, and 500 feet above the equipped aircraft. All three geometries result in small vertical separations at CPA. For the 300- and 500-foot planned vertical separation encounters, the most critical situation occurs when the intruder's planned level-flight time prior to CPA is less than 15 seconds. The BCAS algorithm detection and resolution logic generates a climb for the equipped aircraft while the intruder is still in a descent. The intruder's subsequent level off results in a collision (23 feet of separation for the 500-foot planned CPA).

Vertical acceleration maneuvers by unequipped aircraft are a difficult problem for any collision avoidance algorithm. One method of minimizing the danger of this situation is to provide the pilot with partial positional data on all threats. Alternatively, further improvements in the vertical tracker might improve BCAS performance in this area.

<u>ADVANTAGES OF PARTIAL POSITIONAL DATA.</u>

Active BCAS has the capability of providing range and altitude data on intruders. The altitude data on the intruder can be presented as either the BCAS tracked intruder altitude or as the intruder mode C altitude. Since these advisories may not provide bearing information, they are called partial positional data (PPD's).

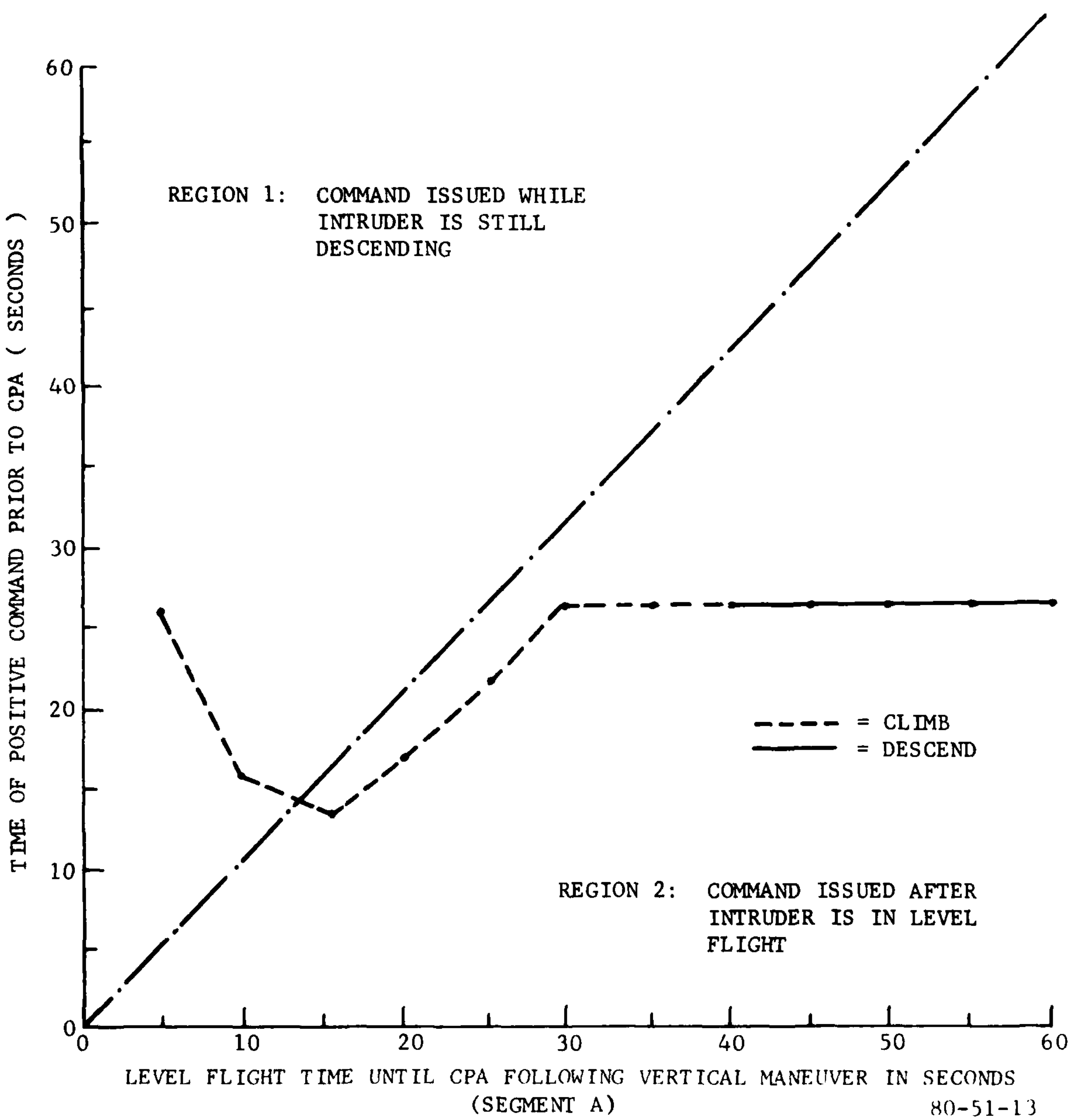

FIGURE 13. EFFECTS OF THE TIME OF THE INTRUDER VERTICAL MANEUVER ON THE TIMING AND SENSE OF POSITIVE COMMANDS

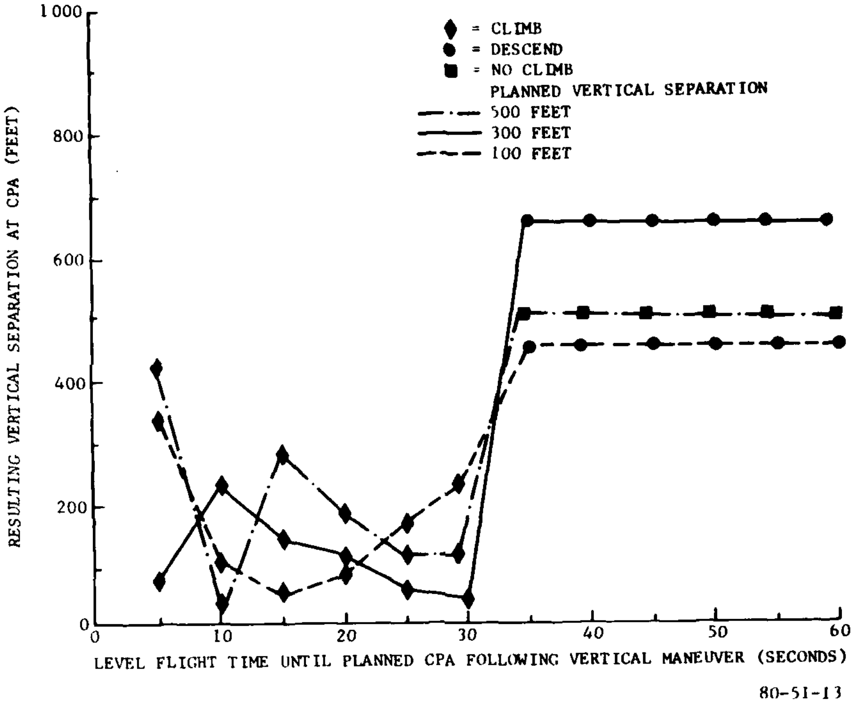

FIGURE 14. COMMAND AND ACHIEVED VERTICAL SEPARATION FOR VERTICALLY ACCELERATING INTRUDERS

The previous analysis of vertically maneuvering intruders indicates that there exists an entire class of encounter geometries in which PPD's displayed in the cockpit could provide critical information for a pilot to satisfactorily resolve a conflict.

Consider the class of geometries where an unequipped intruder is initially on a constant rate vertical trajectory toward a BCAS aircraft in level flight (see figure 15). Without BCAS interaction or any change in the intruder's vertical rate, the intruder aircraft would pass through the BCAS aircraft's altitude well prior to CPA. The current threat logic determines the sense of the escape maneuver (i.e., climb or descend) during the first "hit" in threat volume. The sense selected is then retained throughout the encounter. Vertical maneuvering by the threat aircraft will not change the sense of BCAS commands. Only command severity will be affected. Sometimes, when the intruder's vertical rate changes after BCAS has determined the sense of the command, insufficient vertical separation occurs.

In figure 15 the unequipped intruder is initially descending at a constant rate. The most critical condition occurs when the BCAS vertical track of the intruder indicates that the intruder will pass through the BCAS aircraft's altitude well prior to CPA. This results in a large projected negative vertical miss distance at CPA and causes a climb/no descent sense to be selected. Furthermore, since the magnitude of the vertical miss distance is large, a negative BCAS command, do not descend, is initially generated.

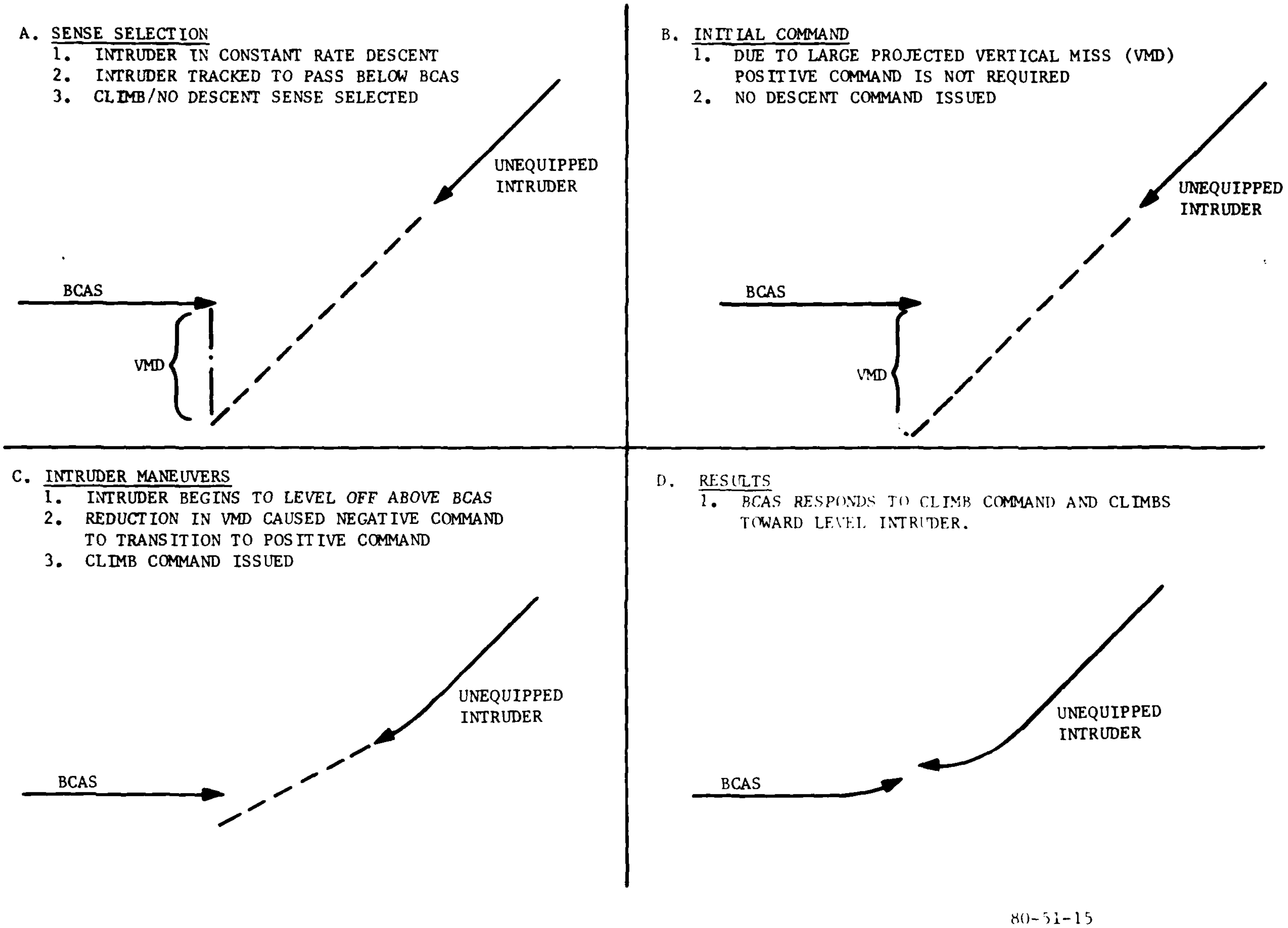

FIGURE 15. BASIC GEOMETRY FOR PARTIAL POSITIONAL DATA EVALUATION

Once the intruder begins to reduce its vertical rate, the projected vertical miss distance decreases. This causes the negative command to transition to a positive climb command. In the final sequence (at the lower right corner of figure 15), the intruder has completed its level off maneuver above the BCAS aircraft. Without additional information in the form of PPD's, the BCAS aircraft will continue to climb toward the level-flight intruder creating a more serious conflict.

The FTEG was programed to simulate encounter conditions defined as follows:

	BCAS	INTRUDER (UNEQUIPPED)
Velocity	360 knots	360 knots
Initial Vertical Rate	0 ft/min	-1,000 ft/min
Crossing Angle	180° head-on encounter	
Initiation of Level-Off Maneuver	26 seconds prior to CPA	
Planned Vertical Separation Following Intruder Maneuver	300 feet	

The BCAS aircraft responded to BCAS commands after a 5-second pilot response delay. The initial descent rate was 1,000 ft/min followed by a 0.25 g level-off maneuver. The example presented does not reflect an extreme vertical maneuver by the intruder.

Table 8 presents the resulting BCAS sequential data along with the intruder's range and altitude information available to BCAS that would comprise the PPD's for the intruder. The data shown would have resulted if a 40-second modified tau were used for displaying PPD's. In table 8, the BCAS aircraft responded to the climb command; the resulting vertical separation at CPA was only 47 feet. The PPD information that would be displayed to the pilot would consist of some combination of the three right-most columns of table 8. Within 10 to 15 seconds after the climb command appeared, regardless of which type of intruder altitude information was displayed, the pilot could recognize that the intruder had leveled off at 10,300 feet. As a result, approximately 200 feet of vertical separation could exist at CPA.

VERTICAL SPEED LIMIT PERFORMANCE.

The vertical speed limit (VSL) performance was measured over a wide range of encounter conditions. The primary objectives of the investigation were to:

1. Evaluate VSL performance.

2. Analyze the effect on VSL performance caused by variations in vertical rates, aircraft velocity, horizontal crossing angle, and horizontal miss distance.

3. Identify the regions (planned vertical separation versus vertical rate) where the VSL's alone will generate sufficient separation; i.e., a transition to a positive or negative command is not required.

The VSL advisories generate separation only in the vertical dimension. Thus, the measures of the vertical separation at CPA between the aircraft due to the VSL advisories are the performance measures of primary interest. In general, the

TABLE 8. SEQUENTIAL BCAS DATA FOR VERTICAL ACCELERATION MANEUVER BY THE UNEQUIPPED INTRUDER

Sequential Encounter Conditions					BCAS Measurements		
Data Cycle	Vertical Separation (feet)	Event Sequence	BCAS Altitude (feet)	Command	Intruder* Altitude (feet)	Mode C** Altitude (feet)	Range (nmi)
49	399	Intruder Descending	10,000	-	10,386	10,400	6.2
50	383	Intruder Descending	10,000	-	10,381	10,400	6.0
51	366	Intruder Descending	10,000	-	10,380	10,400	5.8
52	350	Intruder Descending	10,000	-	10,341	10,300	5.6
53	333	Intruder begins level off	10,000	-	10,314	10,300	5.4
54	316	Intruder begins level off	10,000	Climb	10,296	10,300	5.2
55	308		10,000	Climb	10,286	10,300	5.0
56	300	Intruder level	10,000	Climb	10,281	10,300	4.8
57	300		10,000	Climb	10,280	10,300	4.6
58	300		10,000	Climb	10,281	10,300	4.4
59	292	BCAS Climbing	10,008	Climb	10,284	10,300	4.2
60	283	BCAS Climbing	10,017	Climb	10,287	10,300	4.0
61	266	BCAS Climbing	10,034	Climb	10,290	10,300	3.8
62	250	BCAS Climbing	10,050	Climb	10,293	10,300	3.6
63	233	BCAS Climbing	10,067	Climb	10,295	10,300	3.4
64	216	BCAS Climbing	10,084	Climb	10,296	10,300	3.2
65	200	BCAS CLimbing	10,100	Climb	10,297	10,300	3.0
66	183	BCAS CLimbing	10,117	Climb	10,298	10,300	2.8
67	166	BCAS Climbing	10,134	Climb	10,298	10,300	2.6
68	150	BCAS Climbing	10,150	Climb	10,299	10,300	2.4
69	133	BCAS Climbing	10,166	Climb	10,299	10,300	2.2
70	116	BCAS Climbing	10,184	Climb	10,300	10,300	2.0
71	100	BCAS Climbing	10,200	Climb	10,300	10,300	1.8
72	83	BCAS Climbing	10,217	Climb	10,300	10,300	1.6
73	66	BCAS Climbing	10,234	Climb	10,300	10,300	1.4
74	50	BCAS Climbing	10,250	Climb	10,300	10,300	1.2
75	33	BCAS Climbing	10,267	Climb	10,300	10,300	1.0
76	17	BCAS Climbing	10,283	Climb	10,300	10,300	0.8
77	1	BCAS Climbing	10,299	Climb	10,300	10,300	0.6
78	15	BCAS Climbing	10,315	Climb	10,300	10,300	0.4
79	31	BCAS Climbing	10,331	Climb	10,300	10,300	0.2
80	(CPA) 47	BCAS Climbing	10,347	Climb	10,300	10,300	0.0
81	63	BCAS Climbing	10,363	Climb	10,300	10,300	0.1
82	80	BCAS Climbing	10,380	Climb	10,300	10,300	0.2
83	96	BCAS Climbing	10,396	Climb	10,300	10,300	0.5
84	113	BCAS Climbing	10,413	-	10,300	10,300	0.7
85	129	BCAS Climbing	10,429	-	10,300	10,300	0.9
86	145	BCAS Climbing	10,445	-	-	-	-

*Intruder range and altitude determined by the $\alpha - \beta$ tracker in the TRIACT module.
**Mode C altitude obtained by rounding the TRIACT altitude output.

VSL performance is good when own vertical rate exceeds 1,000 ft/min. The major problems found with VSL resolution of encounters with unequipped threats are:

1. VSL logic permitted short duration cyclic changes in the VSL magnitude.

2. More than 1,000 feet of vertical separation or unnecessay alarms often resulted when (a) the vertical rate of the BCAS aircraft was $\geq$3,000 ft/min or (b) the planned horizontal separation at CPA exceeded 1 mile.

3. The vertical tracker noise resulted in a large number of transitions between VSL, positive, and/or negative commands.

General VSL Performance. The basic geometry used to generate the different encounters is presented in figure 16. All encounters were simulated using sensitivity performance level 5 airspace, the highest BCAS protection level. Throughout the analysis the pilot response delay was fixed at 5 seconds to eliminate performance variations due to BCAS response characteristics. The aircraft response was fixed at 500 ft/min; the maximum acceleration/deceleration allowed was 0.5 g. The analysis presented in this section was designed to measure the effectiveness of Active BCAS vertical speed limit alarms.

The vertical separation generated at CPA due to BCAS alarms is plotted against planned vertical separation (or planned horizontal miss distance) for fixed crossing angle, aircraft velocities, and aircraft vertical rate. On each plot, a "VSL commands only" region is identified. The solid portions of the curves on the plot identify this region. The increase in vertical separation generated in this region is due solely to VSL alarms. The dashed lines on the plots identify the region where commands other than VSL's occur. The absolute value of the observed vertical separation at CPA is used in the plots. Two regions, region 1 and region 2, are also identified in the plots. In region 1, the observed vertical separation is greater then the planned vertical separation. In region 2, the observed vertical separation is less than the planned vertical separation. Planned vertical separation is the separation that would have resulted without BCAS interaction. Region 2 identifies encounter conditions that would cause BCAS to reduce the planned vertical separation. Figure 17 presents the observed vertical separation curves as a function of the planned vertical separation for low vertical rates ($\leq$2,000 ft/min). Similar curves for high vertical rates ($\geq$2,000 ft/min) are presented in figure 18.

Fluctuations in vertical separation are observed for low values ($\leq$300 feet) of planned vertical separation. For low vertical rates, the fluctuations are more frequent. Noneffective VSL alarms are generated for large planned vertical separations and low vertical rates (figure 17). The minimum vertical separation is 425 feet and occurs at point A in figure 18. The conditions associated with the minimum separation had the BCAS descending at 2,000 ft/min so as to be 100 feet below the intruder at CPA. Since the minimum vertical separation is 425 feet, adequate performance is observed throughout the simulation. The area of the "VSL commands only" region is larger for high vertical rates. At low rates, the vertical tracker noise due to quantization affects the measured relative vertical rate. This causes frequent command transitions not only in the magnitude of VSL commands in the "VSL commands only" region, but also early cyclic transitions to negative and/or positive commands in the other region. The noneffective VSL's observed for low vertical rates and high planned vertical separations result because the aircraft vertical rate is less than the magnitude of the VSL's. The size of "the VSL

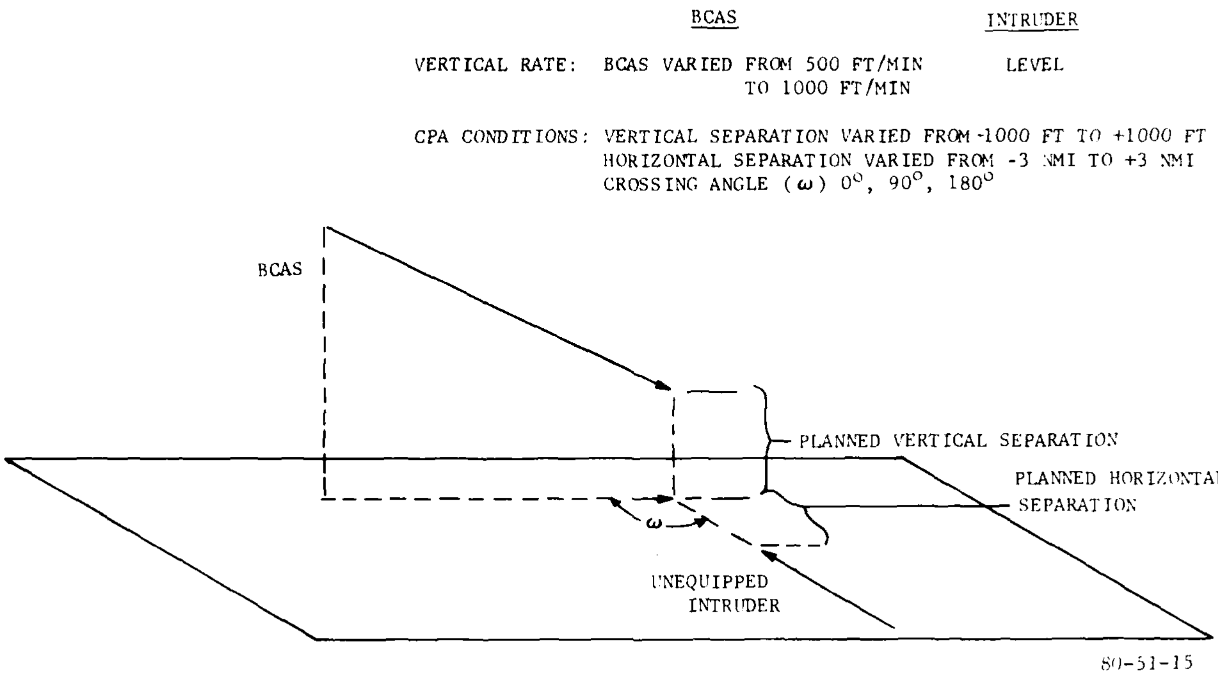

FIGURE 16. BASIC GEOMETRY FOR VSL EVALUATION

commands only" region for high vertical rates increases because (1) the change in the vertical rate caused by the VSL's generates sufficient separation and (2) the thresholds for positive and negative commands are not penetrated.

An analysis was conducted for crossing angles of 0° (tail chase condition), 90°, and 180° (head-on encounter condition). Figure 19 presents the observed vertical separation curves as a function of planned vertical separation. The descent rate is -2,000 ft/min. Figure 20 presents the results associated with a -4,000-ft/min descent. Since the planned horizontal separation is 0 feet, vertical track crossing (negative planned vertical separation) cannot occur in the tail chase equal-velocity encounter.

The vertical separation generated is almost the same for all vertical rates and crossing angles. Ninety-degree crossing angle generates more separation during high vertical rate and negative planned vertical separations (figure 20). Again, the size of the "VSL commands only" region increased as the BCAS aircraft descent rate increased. In figures 19 and 20, asterisks mark conditions which caused a reduction in the planned vertical separation. The reductions were not significant.

The planned horizontal miss distance was varied from -3 to +3 nmi in 0.24-nmi increments. The planned horizontal miss distance is negative if the BCAS aircraft passes behind the intruder. An analysis was conducted for the encounters with 90° crossing angle and 0 feet planned vertical separation.

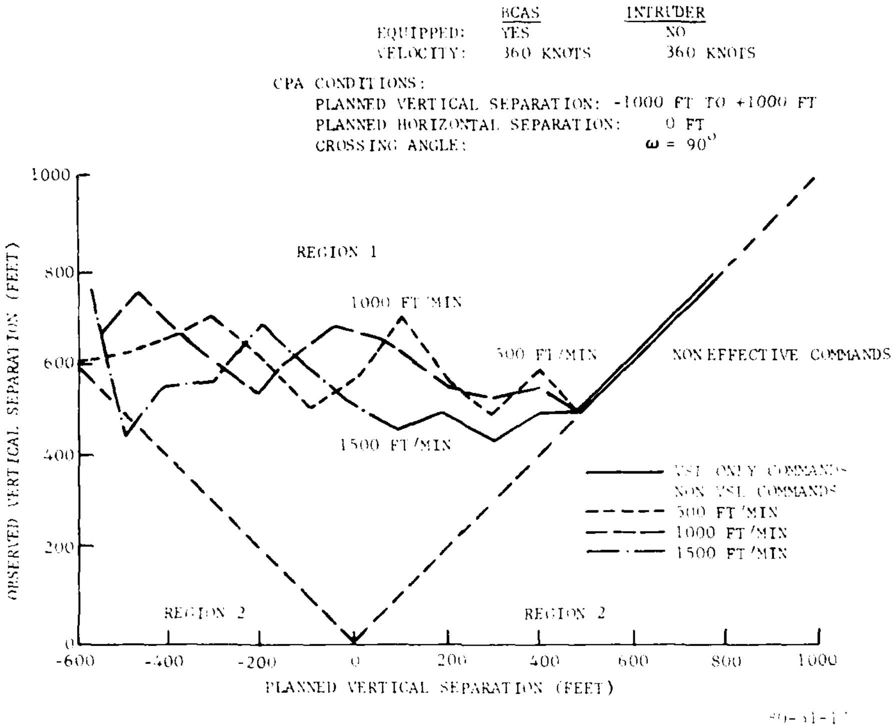

FIGURE 17. VERTICAL RATE EFFECTS ON VSL PERFORMANCE FOR VERTICAL RATES BETWEEN 500 AND 1,500 FEET PER MINUTE

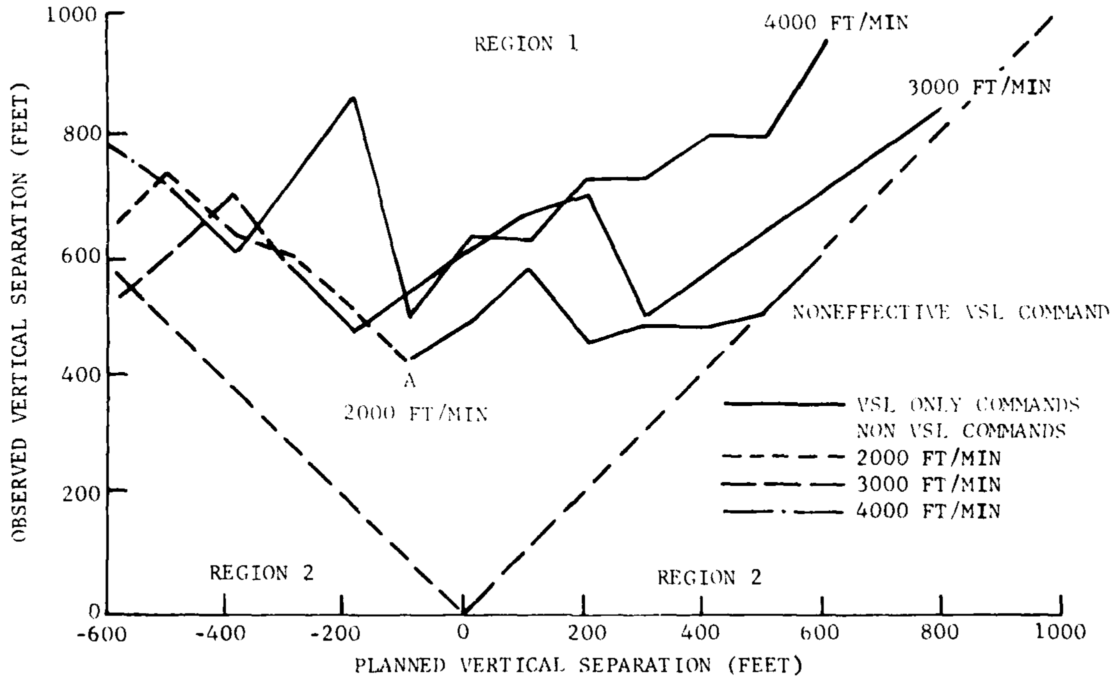

FIGURE 18. VERTICAL RATE EFFECTS ON VSL PERFORMANCE FOR VERTICAL RATES BETWEEN 2,000 AND 4,000 FEET PER MINUTE

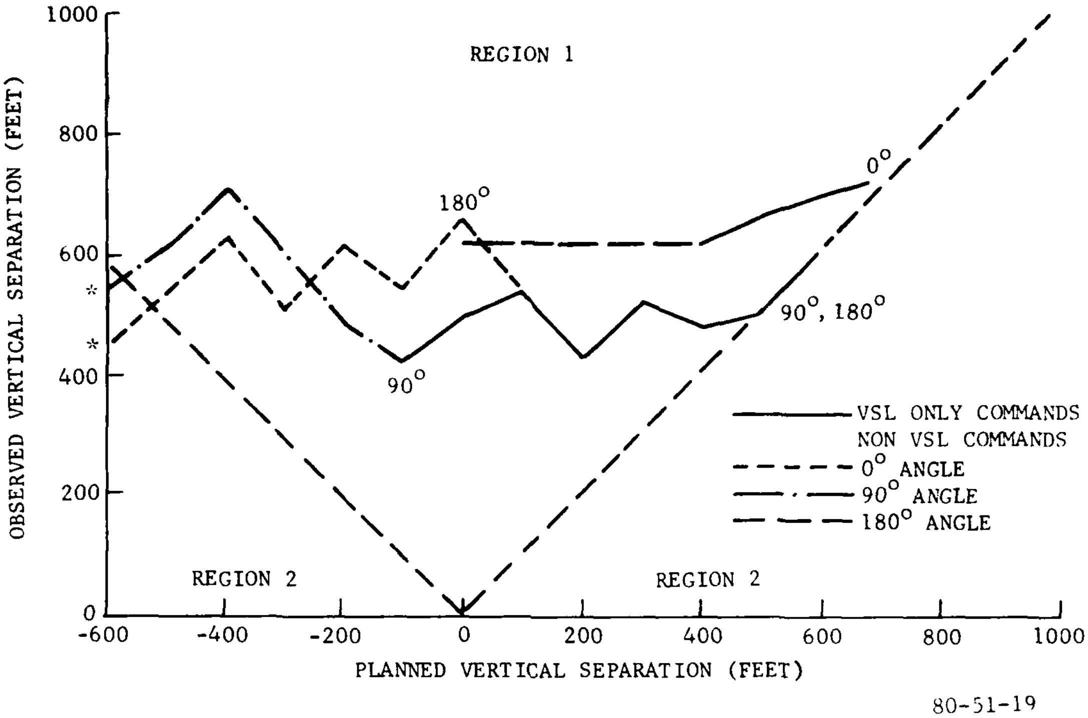

FIGURE 19. CROSSING ANGLE EFFECTS ON VSL PERFORMANCE FOR DESCENT RATE OF 2,000 FEET PER MINUTE

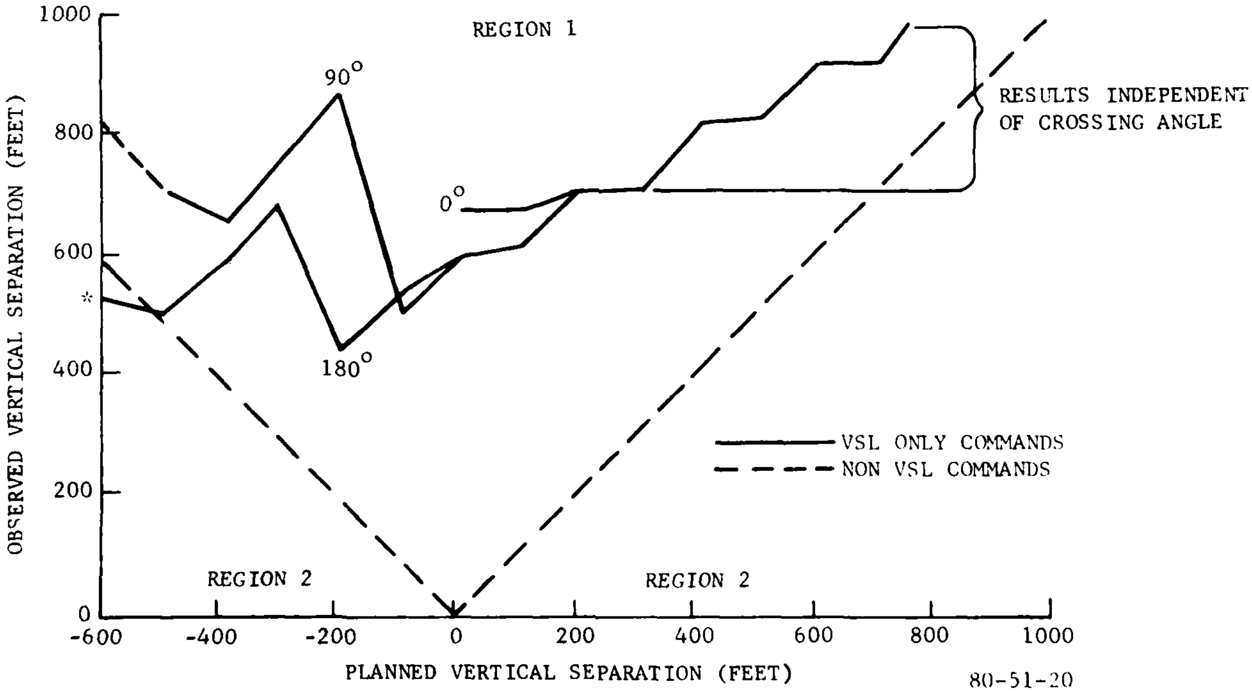

FIGURE 20. CROSSING ANGLE EFFECTS ON VSL PERFORMANCE WITH A HIGH VERTICAL RATE (4,000 FEET PER MINUTE)

Figure 21 presents observed vertical separation curves as a function of planned horizontal miss distance for -4,000- and -2,000-ft/min vertical rates. The abscissa value of zero separated region 1 and region 2. In region 1, the BCAS aircraft passes behind the intruder (planned negative horizontal miss distance); in region 2, the BCAS aircraft crosses in front of the intruder (planned positive horizontal miss distance).

Figure 21 shows that VSL alarms are generated when the BCAS aircraft crosses the intruder path as far as 1.5 nmi ahead of the intruder and 2.75 nmi behind the intruder. The range of the generated vertical separation in these regions varies between 225 to 700 feet. Unnecessary vertical separation is generated due to the BCAS alarms in regions where adequate horizontal separation exists. However, the Active BCAS logic cannot identify the existing safe condition due to its inability to measure horizontal miss distance.

For both vertical rates, the "VSL commands only" region is split into two regions by an area of positive and negative commands. The splits are identified in figure 21. Both splits occurred in region 1 (i.e., negative horizontal miss distance). For the -2,000-ft/min vertical rate case, the split appears at a larger horizontal miss distance when compared to -4,000-ft/min vertical rate error.

The latest BCAS changes include an acceleration model in the logic which selects the VSL magnitude. Prior to this change, a VSL command occurred when $V1 > 8.33$ ft/sec and a negative and/or positive command occurred when

$$V1 \leq 8.33 \text{ ft/sec.}$$

For a level-flight intruder below the BCAS aircraft

$$V1 = (ALIM - A - T1*ZDOWN)/(TRTRU-T1)$$

where TRTRU = - R/RD = - range/range rate.

Both range R and range rate RD are time dependent.

At time t,

$$R(t) = \sqrt{X^2(t) + Y^2(t) + Z^2(t)}$$

where X(t), Y(t), and Z(t) are the relative X, Y, and Z separations of the intruder and BCAS aircraft at time t.

For 90° crossing angle and equal aircraft velocities, the X and Y separations at time t differ only by a constant K. Thus, for negative horizontal miss distance (-K) at time t,

$$X(t) = Y(t)-K$$

$$R(t)^2 = 2*Y(t)^2 + Z(t)^2 + K^2 - 2*K*Y(t)$$

and,

$$TRTRU = - \frac{(2Y^2+K^2-2Y*K+Z^2)^{1/2}}{2Y*\dot{Y}-K\dot{Y}+2Z*\dot{Z}}$$

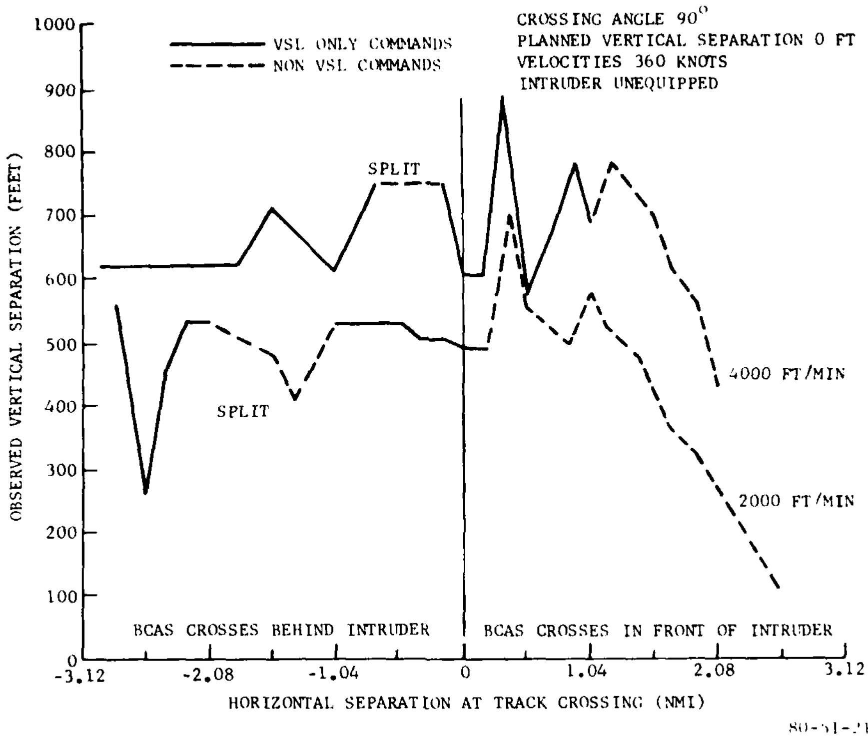

FIGURE 21. HORIZONTAL MISS DISTANCE EFFECTS ON VSL PERFORMANCE

where $\dot{Y}$ and $\dot{Z}$ are relative rates in Y and Z directions respectively. The numerator can never be equal to zero, since R>0 if any horizontal miss distance exists.

Therefore V1 $\longrightarrow 0$ as TRTRU $\longrightarrow \infty$. This implies that non-VSL commands occur when K is in a certain interval. For fixed R, TRTRU $\longrightarrow \infty$ when

$$K \longrightarrow 2*Y + Z*\dot{Z}/\dot{Y}.$$

Hence the split occurs in the "VSL command only" region as K approaches

$$2*Y + Z*\dot{Z}/\dot{Y}.$$

For high vertical rates, this interval shifts towards the right. The split of the -4,000-ft/min vertical rate occurs with smaller miss distances then with -2,000-ft/min vertical rate.

For crossing angles, 0° and 180°, this phenomenon is not expected with the equal-velocity condition. In a zero crossing angle situation with equal aircraft velocities, the crossing of the intruder track behind the intruder is not possible. For all other crossing angles, one would expect a split in the "VSL commands only" region. Additional analysis indicated the largest splits in the VSL-only areas occurred for 90° crossing angles.

The effects of aircraft velocity variation are analyzed by comparing the observed vertical separation for encounters in which the aircraft velocity is varied.

For a given conflict, the BCAS aircraft velocity is equal to the threat aircraft velocity. The results presented in figures 22 and 23 indicate no significant difference in the vertical separation in the "VSL commands only" region.

SHORT DURATION OF VSL's. The current VSL logic only requires that the initial VSL be displayed for 5 seconds (see figures 2-3(d) of reference 1). After this initial 5-second display, the magnitude of the VSL can change every second causing a new display. Several cases of 1-second secondary VSL's have been observed.

A second problem, caused by not requiring a minimum display period for secondary VSL's, is the displaying of a cyclic pattern of 1-second VSL's. The cyclic pattern is caused by vertical tracker noise and own aircraft vertical response to BCAS commands. The requirement of a minimum display period for secondary VSL's would eliminate this problem.

The detection and resolution logic, DRACT, was modified as shown in figure 24 to analyze its effect on the short VSL displays. The change required the VSL alarm to retain the same displayed magnitude for 5 seconds once a magnitude transition occurred. The numerous encounters which had caused short cyclic secondary VSL alarms to occur were repeated. The modification to the VSL display time logic eliminated all short cyclic alarm patterns.

IMPACT ON VSL MAGNITUDE SELECTION. The current Active BCAS logic provides for generation of three VSL command magnitudes. They are limit climb (descent) to 500, 1,000, and 2,000 ft/min. Air carrier aircraft often climb or descend at rates up to 4,000 ft/min. In these cases even the least stringent VSL command (2,000-ft/min limit) can cause a 2,000-ft/min change in the vertical rate of the aircraft. The large magnitude of this change can often result in the generation of excessive vertical separation at CPA. The excessive separation is generated at the expense of larger than necessary deviations from the desired vertical flight profile for the aircraft in question.

The analysis was conducted on BCAS equipped aircraft versus unequipped threats. The VSL performance for equipped threats would at least match the performance reviewed in this section. The analysis is based on an improved VSL function given below.

$$V1 = |ZDOWN| - VACCEL * (TRTRU - T1) + VACCEL * (TZ3)^{1/2}$$

where $$TZ3 = (TRTRU - T1)^2 - 2 * \frac{(ALIM-A-ADOT * TRTRU)}{VACCEL}$$

This new VSL performance function incorporates a vertical acceleration model into the VSL magnitude selection logic.

Two concepts investigated were: (1) What do less stringent VSL commands (magnitudes of 1,000, 2,000, or 4,000 ft/min do to reduce the excessive BCAS commanded separation? and (2) Is adequate separation generated with the new magnitudes? To perform this investigation, the only changes made to the BCAS logic were the changing of the parametric VSL magnitude set (V500=8.33 ft/sec, V1000=16.67 ft/sec, V2000=33.33 ft/sec) to a new magnitude set of (V1000=16.67 ft/sec, V2000=33.33 ft/sec, V4000=66.67 ft/sec). BCAS performance results with the original VSL magnitude set were compared against the BCAS performance results with the new VSL magnitude set.

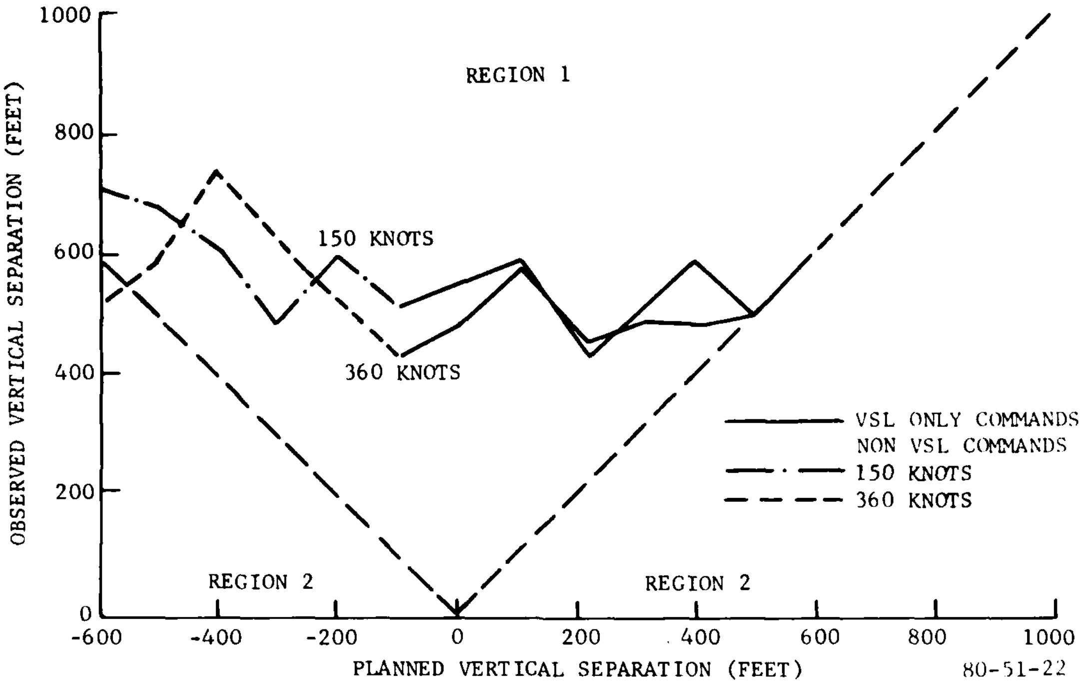

FIGURE 22. VELOCITY EFFECTS ON VSL PERFORMANCE WITH A VERTICAL RATE OF 2,000 FEET PER MINUTE

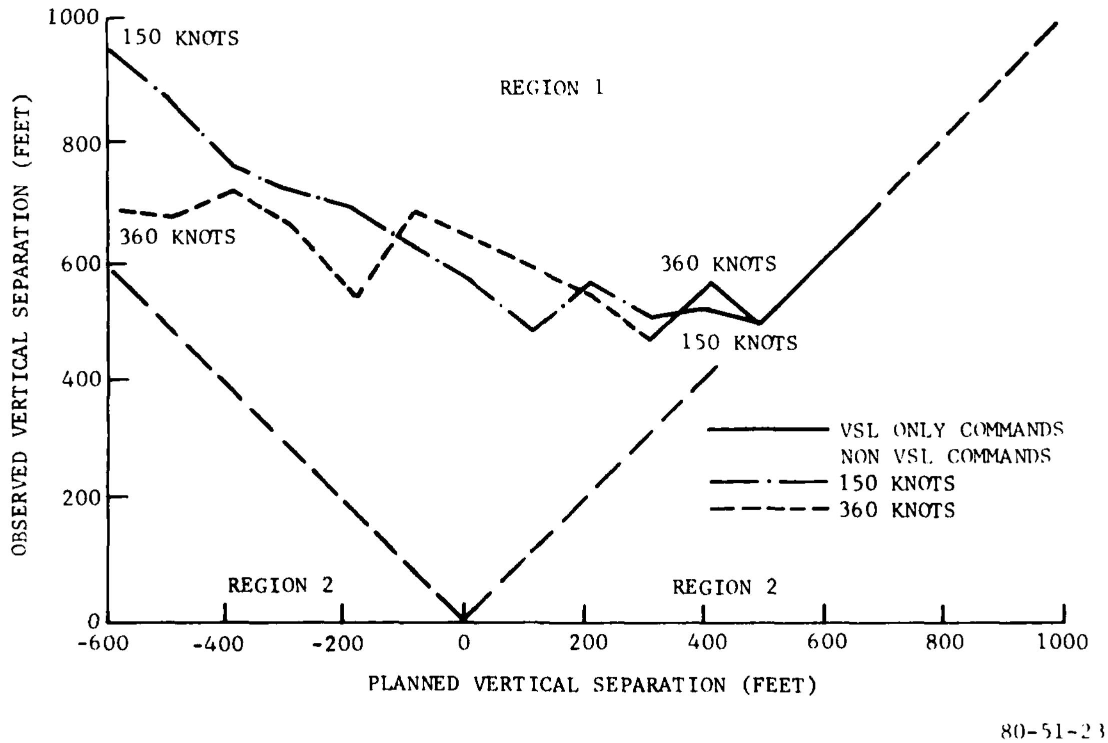

FIGURE 23. VELOCITY EFFECTS ON VSL PERFORMANCE WITH A VERTICAL RATE OF 1,000 FEET PER MINUTE

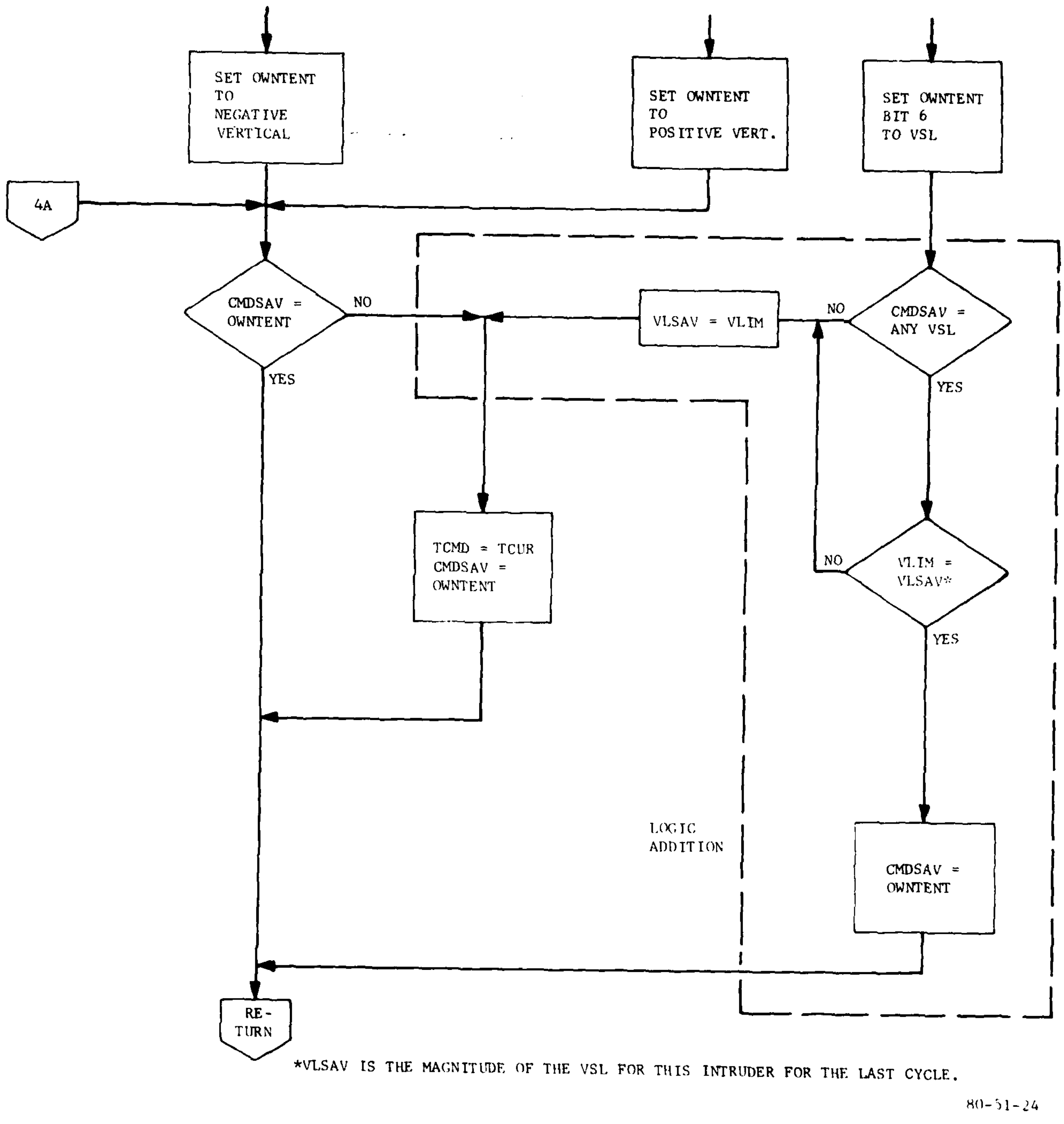

FIGURE 24. DRACT MODIFICATION - VSL DISPLAY TIME

Several different combinations of unequipped intruder vertical rates and BCAS aircraft vertical rates were analyzed. The results for the various combinations are fairly consistent. Figure 25 graphically depicts the encounter conditions on which the results of this section are based.

The encounter conditions shown in figure 25 were simulated with the FTEG using the original VSL magnitudes of 500, 1,000, and 2,000 ft/min. The same conditions were repeated using the new magnitudes of 1,000 2,000, and 4,000 ft/min. The results were analyzed to identify differences in BCAS performance. In no case did the new VSL magnitudes cause BCAS to generate insufficient separation. This could be expected since no logic changes were made that would reduce the occurrences of positive or negative BCAS commands.

Figure 26 depicts the BCAS performance for the original VSL magnitudes. The dashed lines outline the area of increased vertical separation when the planned vertical separation is compared to the separation that results with BCAS. The results are shown for the BCAS aircraft climb rates of 2,000 to 6,000 ft/min in 1,000-ft/min increments. In all cases (for both VSL magnitude sets) adequate vertical separation occurs at CPA.

The solid portions of the plotted curves in figure 26 identify the encounter conditions which are resolved with VSL commands. The dotted portions of the curves indicate regions in which positive and/or negative BCAS commands occur. Figure 27 presents results obtained when the same encounter conditions are simulated using the new VSL magnitude set.

Ideally, BCAS would generate 600 to 800 feet of vertical separation at CPA. This amount of separation would be slightly greater than the visual flight rules (VFR) vertical separation standard. Figure 26 indicates that for the 2,000- and 3,000-ft/min BCAS aircraft climb conditions, BCAS generates a vertical separation (600 to 800 feet) at CPA regardless of the planned vertical separation. For the same climb conditions, figure 27 indicates that for these BCAS climb conditions the new VSL magnitude set causes nearly identical BCAS performance to result. The separation is consistently between 600 and 800 feet.

However, as the BCAS aircraft climb rate is increased beyond 3,000 ft/min, the original VSL magnitude set causes increasingly excessive vertical separations to occur at CPA. The separation at CPA exceeds 1,000 feet for several different individual encounters. With the 6,000-ft/min climb case, the resulting vertical separation exceeds 900 feet (-900 feet) even when the planned vertical separation is as small as -200 feet. The problem with the original VSL magnitude set is that the <u>least</u> restrictive VSL command, limit climb to 2,000 ft/min, causes a large change (4,000 ft/min) in the climb rate for cases where the BCAS aircraft is climbing 6,000 ft/min. Assuming nominal pilot response rates and aircraft acceleration rates, even short duration commands (15 seconds) would cause a 700-foot minimum increase in vertical separation.

The new VSL magnitude set permits less restrictive VSL commands to be chosen for climb rates in excess of 3,000 ft/min. Figure 27 shows that the resulting vertical separation for climb rates in excess of 3,000 ft/min is concentrated between 700 and 800 feet. The resulting separation is greater than 1,000 feet on only one occasion.

	BCAS	INTRUDER
VELOCITY:	250 KNOTS	150 KNOTS
VERTICAL RATE:	VARIED FROM 1,500 FT/MIN TO 6,000 FT/MIN	-1500 FT/MIN

CPA CONDITIONS:
PLANNED VERTICAL SEPARATION: VARIED FROM -1000 FT TO +1000 FT
PLANNED HORIZONTAL SEPARATION: 0 FT
CROSSING ANGLE: $\omega = 90^\circ$
RESPONSE CONDITIONS:
5-SECOND PILOT RESPONSE DELAY
0.25 g ACCELERATION IN RESPONSE TO BCAS COMMANDS

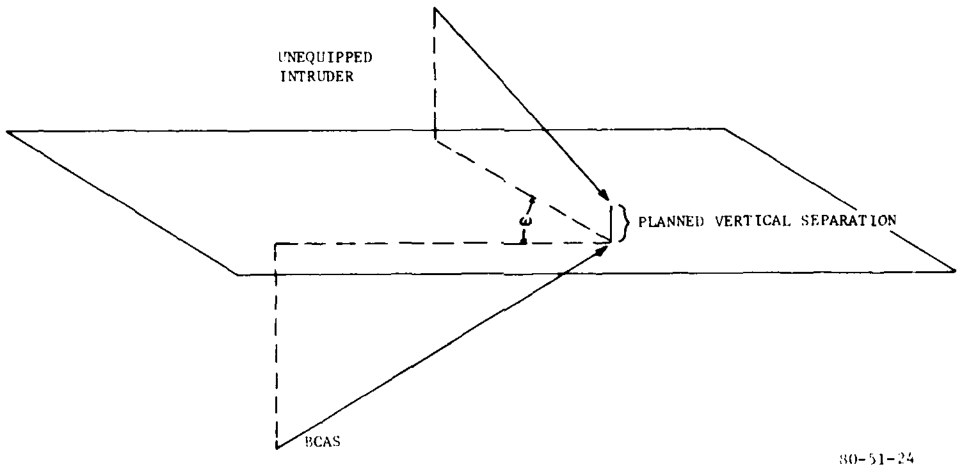

FIGURE 25. ENCOUNTER CONDITIONS FOR VSL MAGNITUDE STUDY

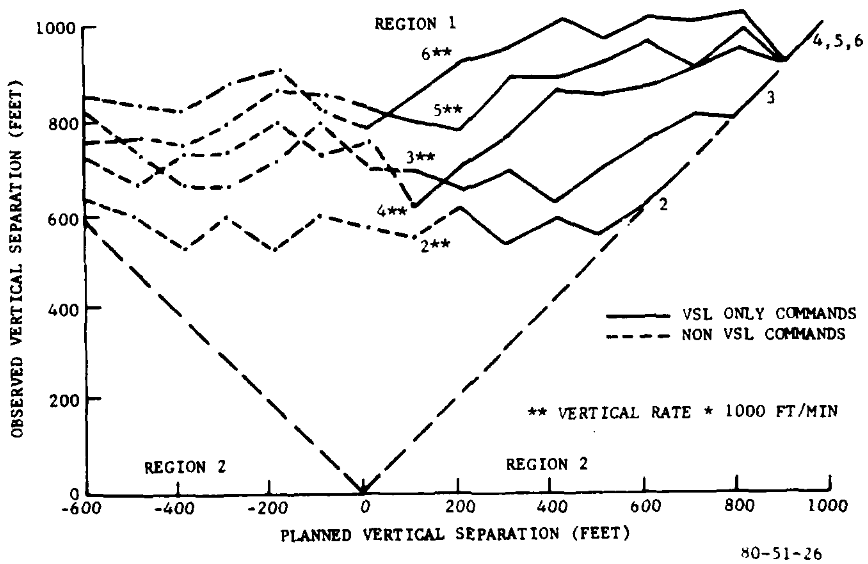

FIGURE 26. VERTICAL SEPARATION AT CPA USING ORIGINAL VSL MAGNITUDE SET (500, 1,000, 2,000 FEET PER MINUTE

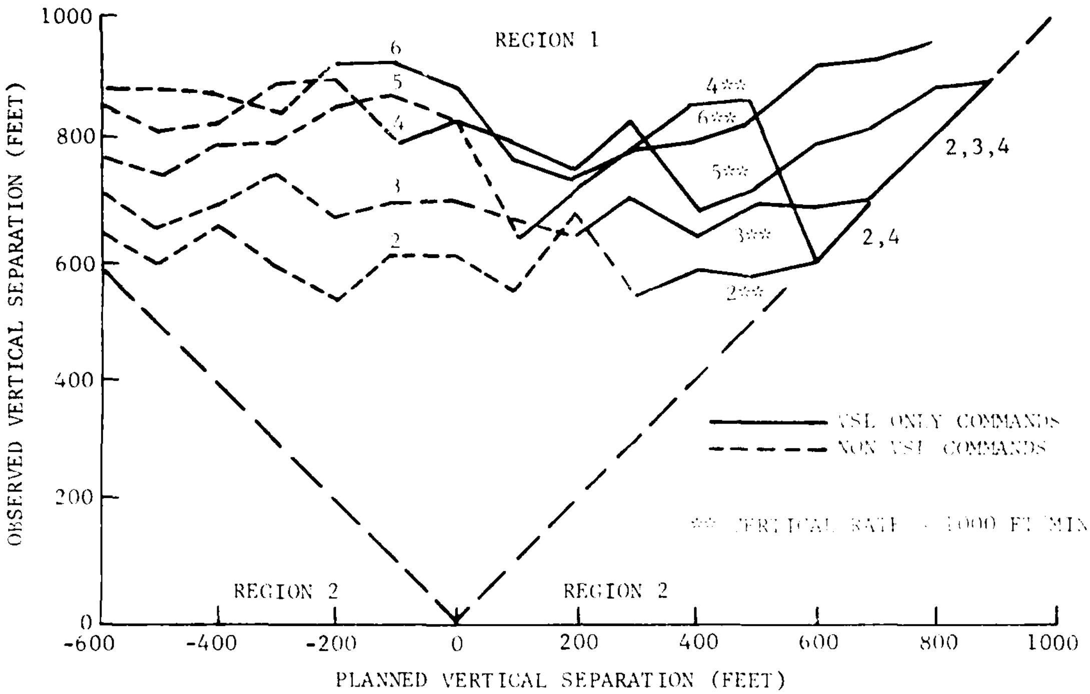

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FIGURE 27. VERTICAL SEPARATION AT CPA USING NEW VSL MAGNITUDE SET (1,000, 2,000 4,000 FEET PER MINUTE)

An analysis of the duration and number of VSL command transitions that occurred was made for both VSL magnitude sets. Tables 9 to 13 present the results of this analysis. Each table reviews the results for a single BCAS aircraft climb rate. Tables 9 and 10 show little difference in the number of command transitions and durations between the VSL magnitude sets.

For climb rates greater than 3,000 ft/min, tables 11 to 13 indicate that the new VSL magnitudes cause longer overall command periods and a greater number of command transitions than does the original set of magnitudes. For 5,000- and 6,000-ft/min climb cases, the original VSL magnitude set consistently causes only one VSL command to occur regardless of the planned vertical separation. For the same climb rates, the new VSL magnitude set causes two or three VSL command transitions to occur when the magnitude of the planned vertical separation is less than 400 feet.

In general, the VSL performance is adequate irrespective of the vertical rate, aircraft velocities, planned vertical separation, and crossing angle. Better performance and larger "VSL commands only" regions are observed for higher vertical rates. However, excessive separation is generated for BCAS aircraft with high vertical rates (3,000 ft/min). A reduction in occurrence of excessive vertical separation could be possible by changing the VSL magnitudes, but this reduction could be obtained only at the cost of longer VSL durations and a higher number of transitions in the VSL commands. The new VSL magnitude set (1,000, 2,000, or 4,000 ft/min) is less restrictive. The benefit may be insignificant due to the increased

TABLE 9. VSL COMMAND DURATION COMPARISON (BCAS AIRCRAFT CLIMBING AT 2,000 FT/MIN)

Planned Vertical Separation (ft)	Original Magnitudes Number of Transitions	Original Magnitudes Average Duration (sec)	Original Magnitudes Total Duration (sec)	New Magnitudes Number of Transitions	New Magnitudes Average Duration (sec)	New Magnitudes Total Duration (sec)
-1,000	0	-	-	-	-	-
-900	1	5.0	5	1	5.0	5
-800	1	5.0	5	1	5.0	5
-700	1	14.0	14	3	6.0	18
-600	1	18.0	18	2	11.0	22
-500	2	8.5	17	2	8.0	16
-400	2	10.0	20	2	9.0	18
-300	2	11.0	22	2	11.0	22
-200	4	6.5	26	4 (-)	6.0	24
-100	4 (+)	7.0	28	4 (+)	7.0	28
0	4 (+)	7.5	30	3 (+)	11.8	35

(+) Positive BCAS command resulted

(-) Negative BCAS command resulted

TABLE 10. VSL COMMAND DURATION COMPARISON (BCAS AIRCRAFT CLIMBING AT 3,000 FT/MIN)

Planned Vertical Separation (ft)	Original Magnitudes: Number of Transitions	Average Duration (sec)	Total Duration (sec)	New Magnitudes: Number of Transitions	Average Duration (sec)	Total Duration (sec)
-1,000	1	5.0	5	0	-	-
-900	1	5.0	5	1	5.0	5
-800	1	5.0	5	1	5.0	5
-700	2	9.5	19	1	14.0	14
-600	2	10.5	21	3	5.7	17
-500	1	18.0	18	2	10.0	20
-400	1	21.0	21	1	20.0	20
-300	4	6.3	25	3	5.7	17
-200	2	11.0	22	2	10.0	20
-100	5	5.6	28	3 (+)	5.7	17
0	3 (+)	6.0	18	3 (+)	6.7	20

(+) Positive BCAS command resulted

TABLE 11. VSL COMMAND DURATION COMPARISON (BCAS AIRCRAFT CLIMBING AT 4,000 FT/MIN)

Planned Vertical Separation (ft)	Original Magnitudes: Number of Transitions	Average Duration (sec)	Total Duration (sec)	New Magnitudes: Number of Transitions	Average Duration (sec)	Total Duration (sec)
-1,000	1	5.0	5	1	5.0	5
-900	1	5.0	5	1	5.0	5
-800	2 (-)	5.0	10	2	5.0	10
-700	1	10.0	10	1	19.0	19
-600	1	11.0	11	1	18.0	18
-500	1	20.0	20	3	7.3	22
-400	1	22.0	22	3	8.0	24
-300	1	26.0	26	2	11.0	22
-200	1	24.0	24	2	12.0	24
-100	1	24.0	24	2	13.0	26
0	4 (+)	5.0	20	4 (+)	5.0	20

TABLE 12. VSL COMMAND DURATION COMPARISON (BCAS AIRCRAFT CLIMBING AT 5,000 FT/MIN)

Planned Vertical Separation (ft)	Original Magnitudes			New Magnitudes		
	Number of Transitions	Average Duration (sec)	Total Duration (sec)	Number of Transitions	Average Duration (sec)	Total Duration (sec)
-1,000	0	-	-	0	-	-
-900	1	5.0	5	1	5.0	5
-800	1	9.0	99	1	9.0	9
-700	1	10.0	10	1	9.0	9
-600	1	11.0	11	1	19.0	19
-500	1	12.0	12	1	20.0	20
-400	1	13.0	13	2	13.0	26
-300	1	15.0	15	3	5.0	15
-200	1	15.0	15	2	7.5	15
-100	1	17.0	17	2	9.0	18
0	1	21.0	21	2	12.0	24

TABLE 13. VSL COMMAND DURATION COMPARISON (BCAS AIRCRAFT CLIMBING AT 6,000 FT/MIN)

Planned Vertical Separation (ft)	Original Magnitudes			New Magnitudes		
	Number of Transitions	Average Duration (sec)	Total Duration (sec)	Number of Transitions	Average Duration (sec)	Total Duration (sec)
-1,000	0	-	-	0	-	-
-900	0	-	-	0	-	-
-800	1	10.0	10	1	10.0	10
-700	1	11.0	11	1	11.0	11
-600	1	12.0	12	1	13.0	13
-500	1	12.0	12	1	13.0	13
-400	1	14.0	14	1	15.0	15
-300	1	14.0	14	1	22.0	22
-200	1	15.0	15	1	24.0	24
-100	1	12.0	12	2	14.0	28
0	1	14.0	14	3	7.0	21

number of VSL command transitions. At lower BCAS aircraft vertical rates (<2,000 ft/min), tracker noise affects the measured vertical rate. This results in many command transitions. Due to the lack of horizontal miss distance information, BCAS interaction is observed for horizontal separations of up to 3 nmi at CPA. VSL commands generate excessive separation in this region. Current Active BCAS logic cannot identify the safe condition due to horizontal miss distance.

GENERAL PERFORMANCE.

In this section, three types of encounters are discussed: (1) abrupt horizontal maneuvers by unequipped threats, (2) linear encounters with aircraft in level flight, and (3) linear encounters with both aircraft climbing and/or descending. The BCAS response characteristics are fixed throughout the analysis in this section. The aircraft response rate to positive commands is 1,000 ft/min; the pilot response delay is 5 seconds; and the maximum acceleration/deceleration allowed is 0.5 g.

ABRUPT HORIZONTAL MANEUVER. The Active BCAS logic uses a tau distance modifier (DMOD) to provide increased protection against abrupt horizontal maneuvers of a threat aircraft. The current value of DMOD is 1 nmi for performance level 5 (highest protection level). The adequacy of the DMOD value is analyzed in this section. The threat is unequipped in this analysis.

The basic geometry analyzed is shown in figure 28. The intruder aircraft is paralleling the course of the BCAS aircraft. A horizontal maneuver toward the BCAS aircraft is begun by the intruder sometime prior to CPA. All geometrical variations are designed so that when the intruder completes the maneuver, the pair will be on a collision course with a 90° crossing angle. Without BCAS interaction, all tested encounters result in collision.

Several variations are made to the basic geometry. The first varies the amount of time from the intruder's turn completion to CPA. This time is varied from 0 seconds (i.e., turn completion and collision are simultaneous) to 50 seconds. In the latter case, the turn is completed well prior to BCAS detection. BCAS sees this encounter as a purely linear encounter.

The second condition that was varied is the turn rate of the unequipped aircraft. The turn rate is either 6°/sec (twice standard rate), 3°/sec (standard rate), or 1.5°/sec (half standard rate). The variation in the turn rate permits the analysis of (1) the effect of the turn rate on separation and (2) the effect of varying the horizontal offset distance prior to turn on the resulting separation. To more fully exercise the new unequipped intruder sense choice logic, the climb rate of the BCAS aircraft is set to 300 ft/min throughout the encounter. Similarly, the unequipped intruder's climb rate is set at 500 ft/min. The BCAS aircraft climbs at 300 ft/min until a BCAS command occurs. The BCAS aircraft then responds to the BCAS command.

Throughout the study, the BCAS response characteristics are constant; i.e., the pilot response delay is fixed at 5 seconds. After this initial 5-second delay, the BCAS aircraft accelerates in the commanded direction at 0.25 g (8 ft/sec^2) until a 1,000-ft/min climb or descent is established for positive commands. With BCAS interaction, both aircraft are climbing throughout the encounter. With the intruder climbing at a higher rate, the proper choice should be a descent for all encounters.

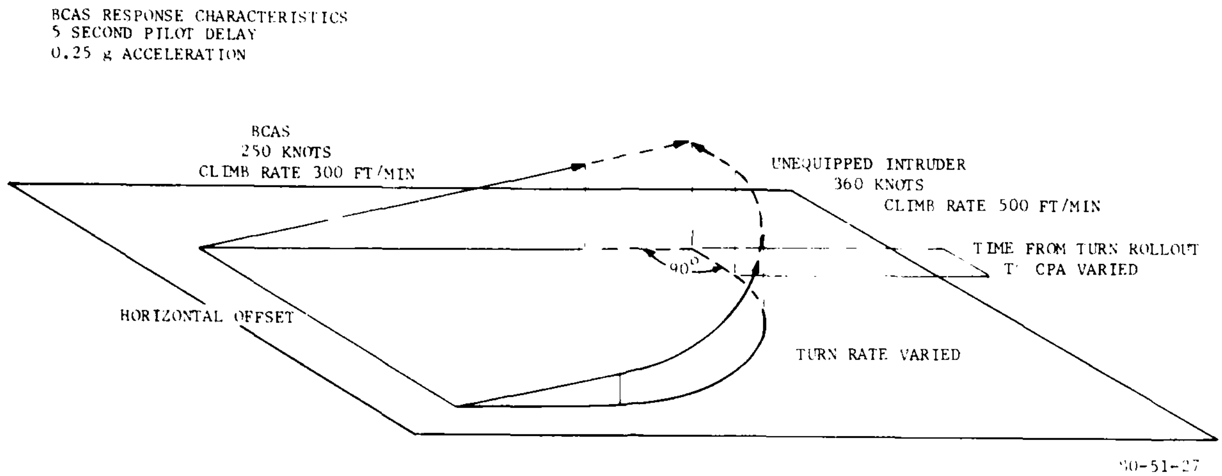


FIGURE 28. BASIC GEOMETRY FOR HORIZONTAL MANEUVER EVALUATION

Two separate cases are analyzed. In the first case, the intruder speed is higher than the BCAS aircraft (360 knots versus 250 knots). For this case, the 6°/sec turn rate represents a very strong horizontal maneuver. The load factor, G, in a turn is defined as the ratio of lift produced in banked flight to weight. The load factor in a constant rate turn can be expressed as a function of the rate of turn and velocity (reference 9) as follows:

$$G = \left\{ \cos \left[\arctan(r*v/1091) \right] \right\}^{-1}$$

where: r = rate of turn in degrees per second

v = velocity in knots

The load factor, G, is 2.22 for the 6°/sec turn. Similarly, the standard rate turn yields G=1.41; the half standard rate turn yields G=1.11. As can be seen, the 360-knot aircraft turning at 6°/sec represents an extreme maneuver.

For the second case analyzed, the intruder's speed is less than the BCAS aircraft's speed (150 knots versus 250 knots). The major difference in the two cases is that in the first case, the high speed intruder has a positive range rate (no closure), relative to the BCAS aircraft prior to horizontal maneuvering, regardless of the horizontal offset distance. As a result, detection cannot occur prior to horizontal maneuvering unless DMOD is penetrated. This is not true in the second case. For the low speed intruder, a negative range rate (closure) relative to the BCAS aircraft exists prior to horizontal maneuvering. This permits earlier BCAS detection.

Two characteristics of BCAS protection are analyzed: (1) the vertical separation at CPA and (2) the timing of alarms prior to CPA.

The separation achieved with the various conditions and the high speed intruder is shown in figure 29. The BCAS protection provided for the three turn rates is compared. The resulting separation is plotted as a function of the time from turn completion to CPA. When the time from turn completion to CPA equals or exceeds 35 seconds, the performance is uniform for all turn rates (480-foot observed vertical CPA). This is expected since for all these encounters, the turn is completed prior to alarm generation. This results in the encounters being treated as simple linear encounters. For these cases, the turn had no effect on BCAS performance.

An interesting point should be made while reviewing figure 28. Although BCAS detection follows turn completion and the encounters are purely linear at this time (30 seconds until CPA), the resulting separation is different for the various turn rates. Although the intruder is in linear flight when the initial alarm occurs, the alarm is delayed as the turn rate increases. This results because of range tracker lag. With the higher turn rates, the range tracker yields lower range closure rate estimates as the intruder rolls out of its turn. The lower tracked closure rates result in alarm delays.

In general, when times from turn completion to CPA are less than 30 seconds, the separation is reduced as the turn rate increases. In the cases of half standard rate turns, the separation always exceeds 300 feet. For standard rate turns which represent fairly strong horizontal maneuvers for a 360 knot aircraft, the resulting separation always exceeds 200 feet. For the twice standard rate turn, the separation is insufficient when time from turn completion to CPA is 10 seconds or less.

The separation differences between the three curves on figure 29 are attributable directly to the timing of initial alarms. Figure 30 shows how the alarm times decrease significantly as the turn rate is increased. For the half standard rate turn, the minimal horizontal offset distance that can occur and still permit a 90° turn to be completed is 2.88 nmi. These conditions result in an alarm 21 seconds prior to CPA. The minimum horizontal offset with a standard rate turn is 1.77 nmi permitting an alarm to occur 17 seconds prior to CPA. For the highest turn rate, the minimum horizontal offset distance is 1.03 nmi, causing an alarm to occur only 9 seconds prior to CPA. This late alarm results in only 69 feet vertical separation at CPA.

Interestingly, a 360-knot intruder turning at 6°/sec, so that turn completion and CPA are simultaneous, results from a horizontal offset distance of 1.03 nmi. If all the geometrical conditions are held constant except for the turn rate which is increased, the horizontal offset distance is less than 1 nmi, the value of DMOD. This will cause an earlier alarm to occur and an increase in the resulting miss distance.

In figure 30 the three points marked with asterisks identify the initial alarm times and horizontal offsets associated with scenarios in which turn completion occurs 10 seconds prior to CPA. For these three points, there is a significant difference in the initial alarm times (15 seconds for the twice standard rate turn, 19 seconds for the standard rate turn, and 22 seconds for the half standard rate turn). When the range is greater than DMOD, the initial alarm is controlled by the relative range rate. Initially, the range rate is positive, and no alarm occurs. To obtain a negative range rate (closure), some portion of the turn must be completed by the intruder. In the three cases, approximately the same amount of turn

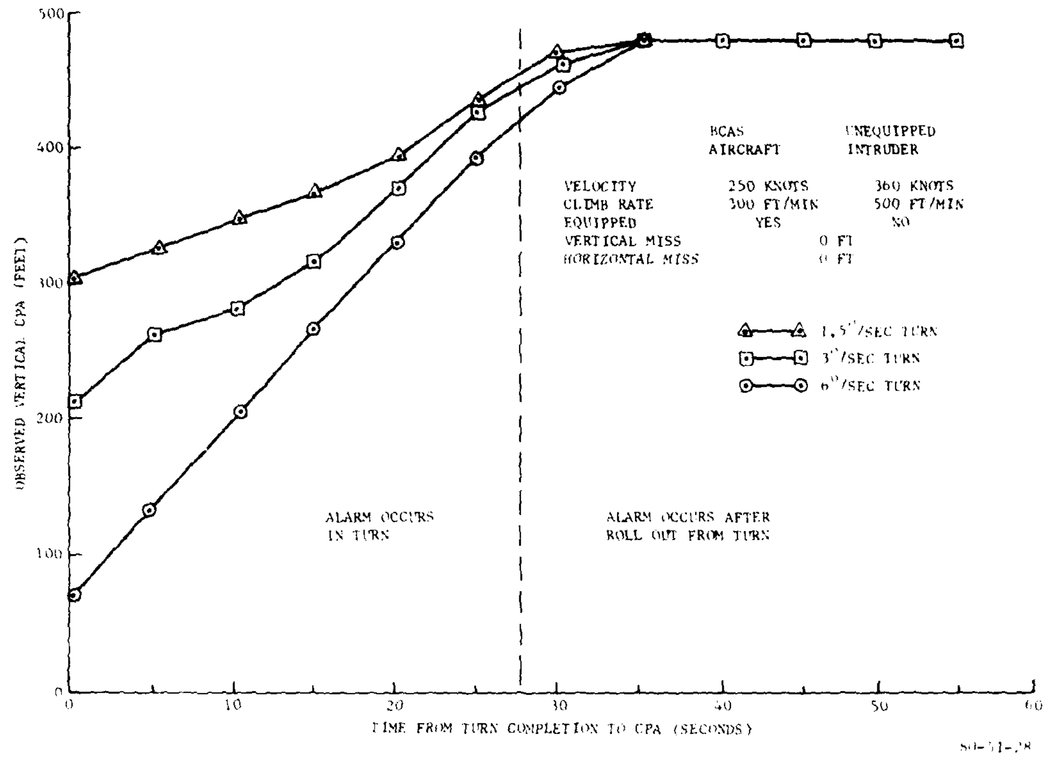
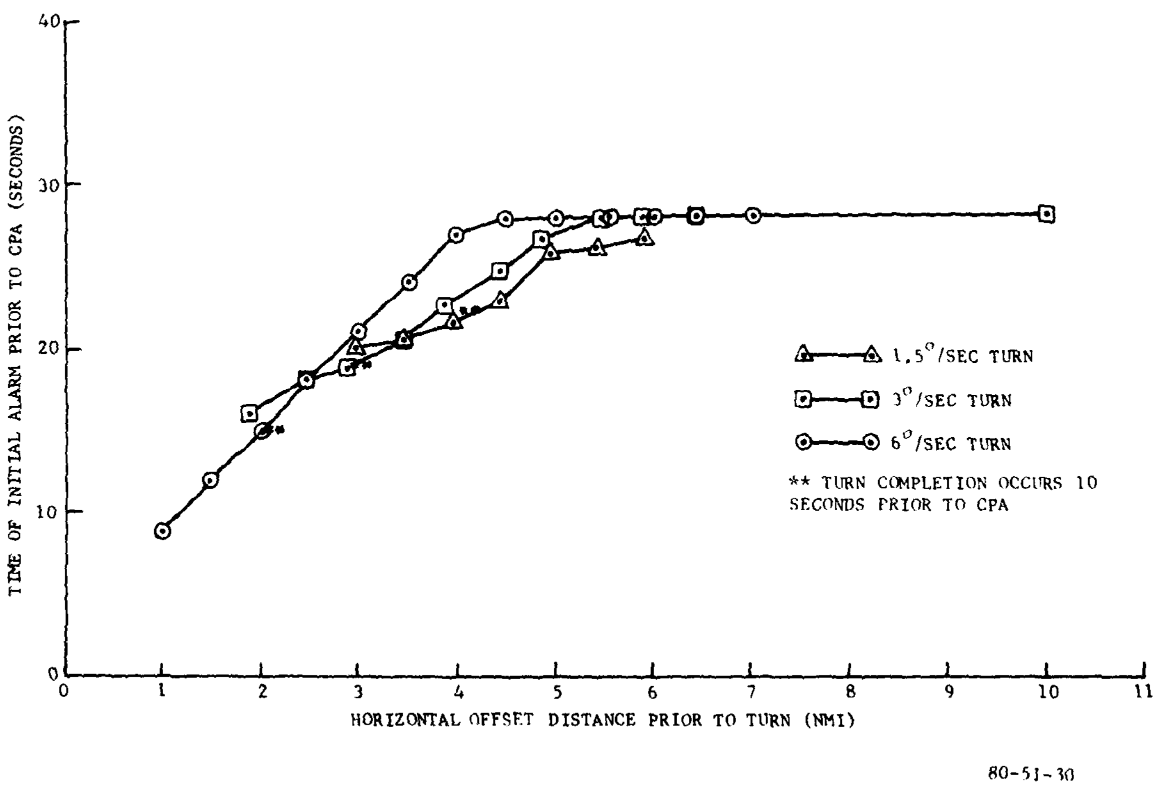


FIGURE 29. VERTICAL SEPARATION FOR THE HIGH SPEED UNEQUIPPED INTRUDER



FIUGRE 30. ALARM TIMING FOR THE HIGH SPEED UNEQUIPPED INTRUDER

is completed prior to the alarm (60° for the twice standard rate turn, 63° for the standard rate turn, and 70° for the half standard rate turn). The difference in initial alarm times results from the fact that the turn will be completed in 5 seconds for the highest turn rate and in 12 seconds for the lowest turn rate. The additional 7 seconds of alarm time results in the significant increase in separation.

The crossover of the curves on figure 30 can be explained as follows. For a fixed time from turn completion to CPA, the horizontal offset distance must increase as the turn rate is decreased. This causes the curves to shift right as the turn rate decreases.

The interaction between turn rate and horizontal offset distance prior to turn and its effect on the observed vertical CPA is shown in figure 31. The small vertical separation, associated with the highest turn rate and the smallest offset distances, is due to the late alarm. The pattern of resulting observed vertical CPA's is attributable to the pattern of initial alarm times shown in figure 30.

The results of the low speed intruder encounters are presented in figure 32. As before, the observed vertical CPA's are uniform when the time from turn completion to CPA equals or exceeds 35 seconds. For these cases, the separation is 418 feet (figure 32) versus 480 feet (figure 29) for the high speed scenario. The reduction in separation results because initially a negative command occurs for the low speed intruder, while the high speed intruder causes an immediate positive command for these conditions. The negative command results because TRTRU (-R/RD) is higher for the low speed intruder when threat volume is initially penetrated. The higher value of TRTRU (more than the value of TVPCMD) causes an overestimation of the projected vertical miss distance at CPA. For the low speed intruder, VMD is greater than ALIM, the positive command threshold, which permits the negative command to occur. A transition to a positive command follows the initial negative command selection. The command sequence does not significantly reduce the achieved separation.

As is the case for the high speed intruder, although BCAS detection occurs after turn completion (30 seconds remain from turn completion to CPA), less separation results for the higher turn rates. While the intruder is in linear flight when detected for all three turn rates, range tracker lag causes a delay in alarms for the higher turn rates. When the time from turn completion to CPA is less than 30 seconds, separation decreases with the decrease in time to CPA. Only one encounter results in an observed vertical CPA of less than 200 feet. With only 5 seconds between turn completion and CPA for the high turn rate, the separation is only 181 feet. One interesting fact presented in figure 32 is that when CPA and turn completion are simultaneous for the high turn, a significant increase occurs in observed vertical CPA (378 feet). The increase occurs because the BCAS aircraft has a negative range rate established for the low speed intruder (150 knots versus 250 knots) well prior to horizontal maneuvering by the intruder. The horizontal offset distance is only 0.4 nmi, which is much less than DMOD. The small offset distance and the negative range rate permit the initial alarm to occur 28 seconds prior to CPA. This fact is verified in figure 33. Hence, the alarm occurs 13 seconds before the intruder begins to turn.

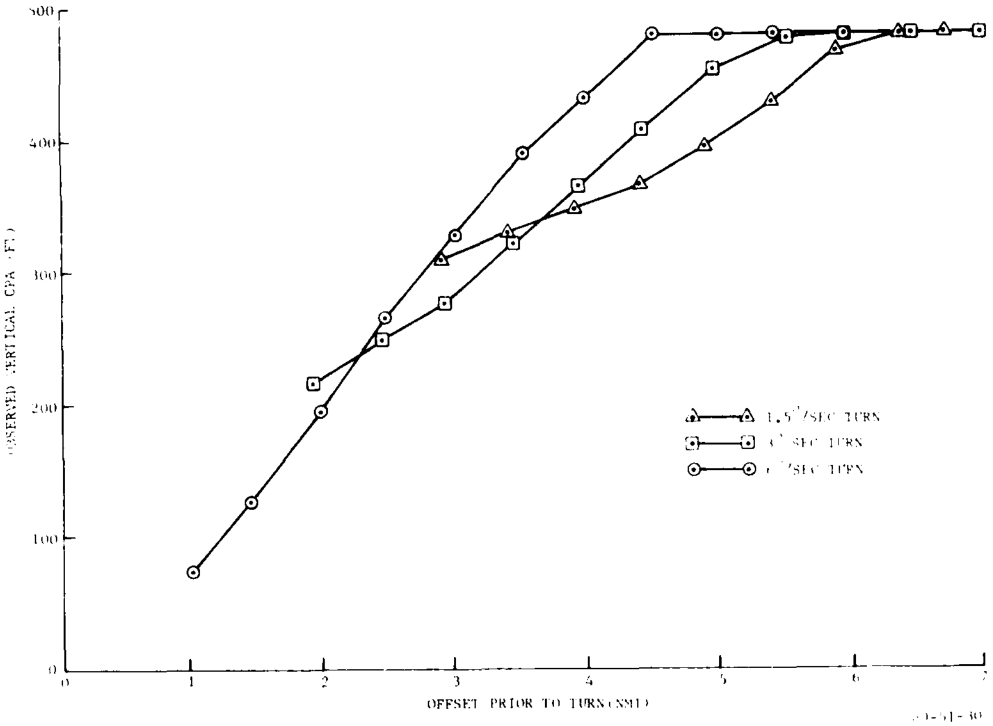


FIGURE 31. OFFSET TURN RATE INTERACTION EFFECT ON VERTICAL MISS DISTANCE (HIGH SPEED THREAT)

A review of figure 33 shows basically the same pattern of alarm times as seen in the high speed intruder case. Several minor differences should be discussed. For the linear encounters, the initial alarms occur uniformly 30 seconds prior to CPA. This is 4 seconds earlier than in the high speed case. The difference is due to the interaction between DMOD and a smaller value of -R/RD for the low speed intruder. As reviewed before, the resulting separation for the linear encounters is slightly less in the low speed intruder cases because, initially, negative commands are selected. Again an increase in the alarm length occurs when the horizontal offset distance is significantly less than DMOD.

In figure 34 the interaction effect between horizontal offset distance and turn rate on observed vertical CPA is shown. As in the high speed case, the pattern is directly attributable to the pattern on initial alarm timing shown in figure 33. The smaller range of horizontal offset distances for the low speed intruder reflects the decrease in distance that can be covered by the low speed intruder.

With the performance level 5 range modification (offset) of 1 nmi, the review of the above results indicates good BCAS performance for a wide range of horizontally maneuvering unequipped intruders. The vertical separation is significantly less than 200 feet for only one encounter. This occurred for a late, high rate horizontal maneuver by a high speed intruder. Throughout the current analysis, the proper sense choice was always selected. Additional analysis for performance

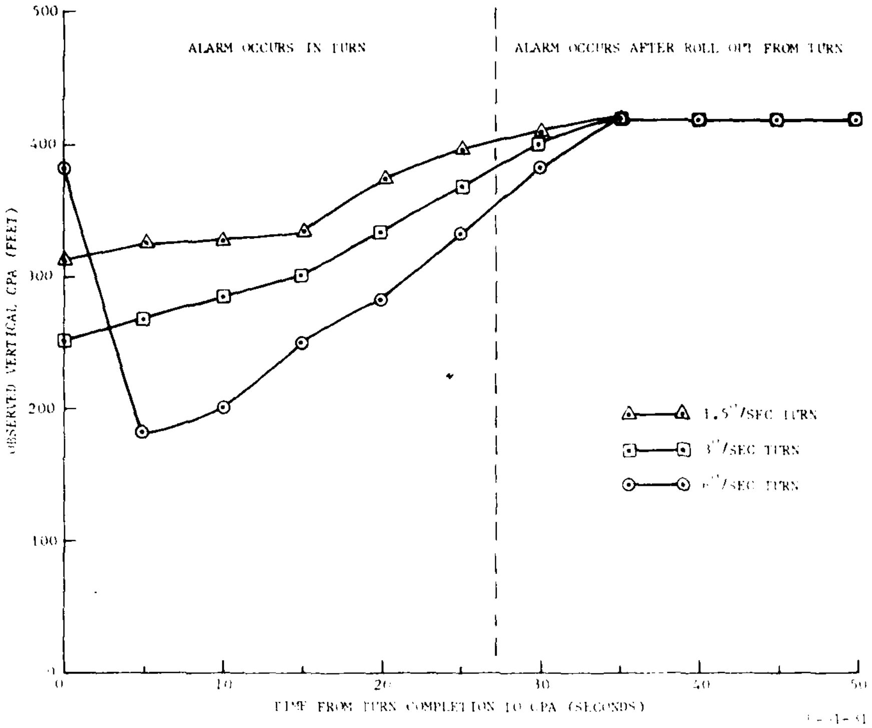
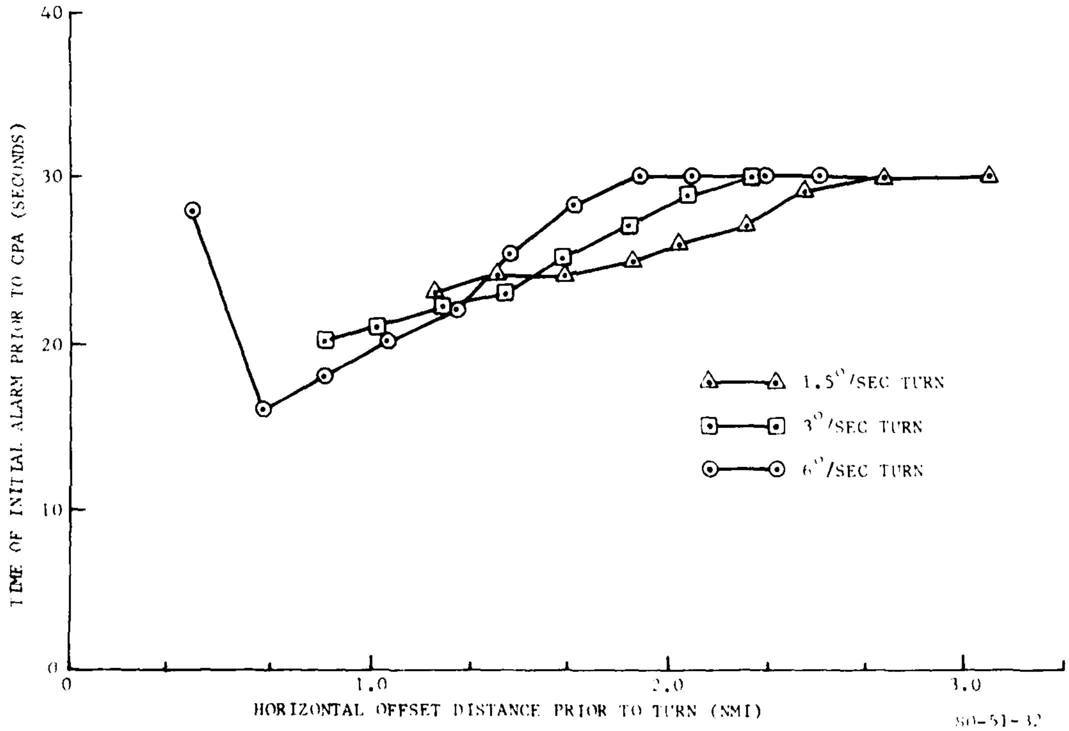


FIGURE 32. VERTICAL SEPARATION FOR THE LOW SPEED INTRUDER



FIUGRE 33. ALARM TIMING FOR THE LOW SPEED UNEQUIPPED INTRUDER

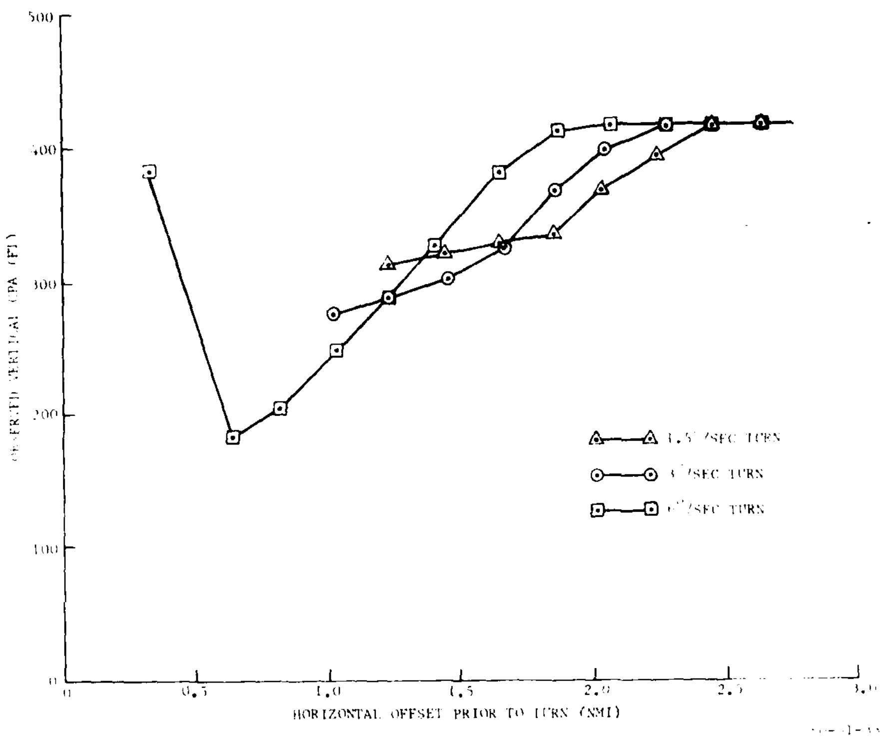


FIGURE 34. OFFSET TURN RATE INTERACTION EFFECT ON VERTICAL MISS DISTANCE (LOW SPEED THREAT)

level 3 DMOD has shown adequate performance for encounters with velocities represenative of the terminal environment.

Studies have been made to determine the effect on observed vertical CPA caused by variations in the crossing angle for horizontally maneuvering intruders. In general, analysis indicates an increase in separation as the crossing angle is increased. This is expected because an increase in the crossing angle results in higher closure rates earlier in the scenario. As the crossing angle is decreased below 90°, separation again increases because the reduction in the horizontal closure rate permits more time for BCAS action.

Linear Encounters With One Aircraft In Level Flight. The investigation of the performance of Active BCAS logic during linear encounters is discussed in this section. Previous analysis has shown that the performance of Active BCAS logic during linear encounters in which BCAS aircraft have high vertical rates is excellent (VSL Performance section). Therefore, the analysis focuses on encounters in which BCAS aircraft have low vertical rates or are in level flight.

Two basic geometries are used for the analysis. In the first geometry (figure 35) a BCAS aircraft is flying level, while the unequipped threat aircraft is descending from above at a known rate. Bot' ..rcraft have equal velocities, and the horizontal crossing angle is 90°. The ometry is modified by varying the

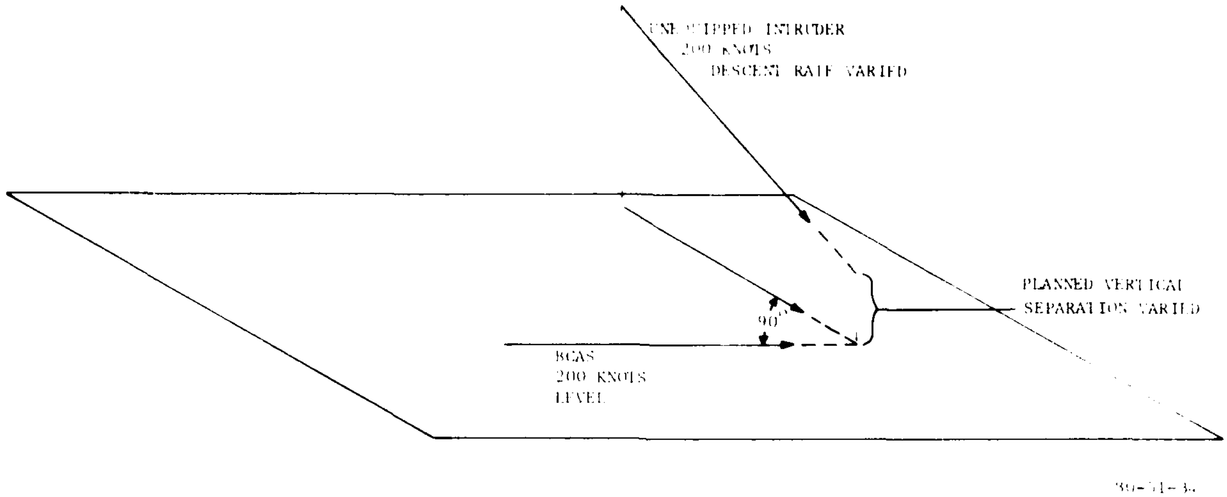


FIGURE 35. BASIC GEOMETRY FOR LINEAR ENCOUNTER EVALUATION

vertical rate of the threat aircraft from -500 through -4,000 ft/min. The resolution (observed vertical separation) is plotted as a function of the planned vertical separation. The planned vertical separation was varied from -1,000 to +1000 feet in 100-foot increments.

Figure 36 presents the plots of observed vertical separation against planned vertical separation for the linear encounter which has the BCAS aircraft in level flight and the unequipped threat descending. The vertical rate of the unequipped aircraft is set at -500 and -1,000 ft/min. The data points labeled by the letter "I" indicate incorrect sense choice. The BCAS generated vertical separation is larger than the planned vertical separation in all cases. Marginal separations are observed at two points: (1) -500 ft/min vertical rate and -200-foot planned vertical separation and (2) -1,000 ft/min vertical rate and -100-foot planned vertical separation. At both points, incorrect sense is chosen due to tracker error. This problem was discussed in the previous section on tracker performance. Figure 37 presents the observed vertical separation versus planned vertical separation plots for vertical rates -2,000 and -4,000 ft/min. Adequate performance is observed at all points.

Vertical rates greater than 1,500 ft/min for BCAS aircraft are not considered in the analysis of level-flight unequipped threats versus maneuvering BCAS aircraft. The analysis of such encounters was presented in the VSL Performance section. The performance was found to be adequate. Figure 38 presents the observed vertical separation versus planned vertical separation plots for BCAS aircraft vertical rates -500 ft/min and -1,500 ft/min. All plots show adequate separation at all planned vertical separation points.

The performance of Active BCAS during linear encounters with an unequipped threat is sufficient. Wrong sense choices, due to vertical tracker error, occur for low vertical rates. Wrong sense choices need not necessarily result in insufficient separation.

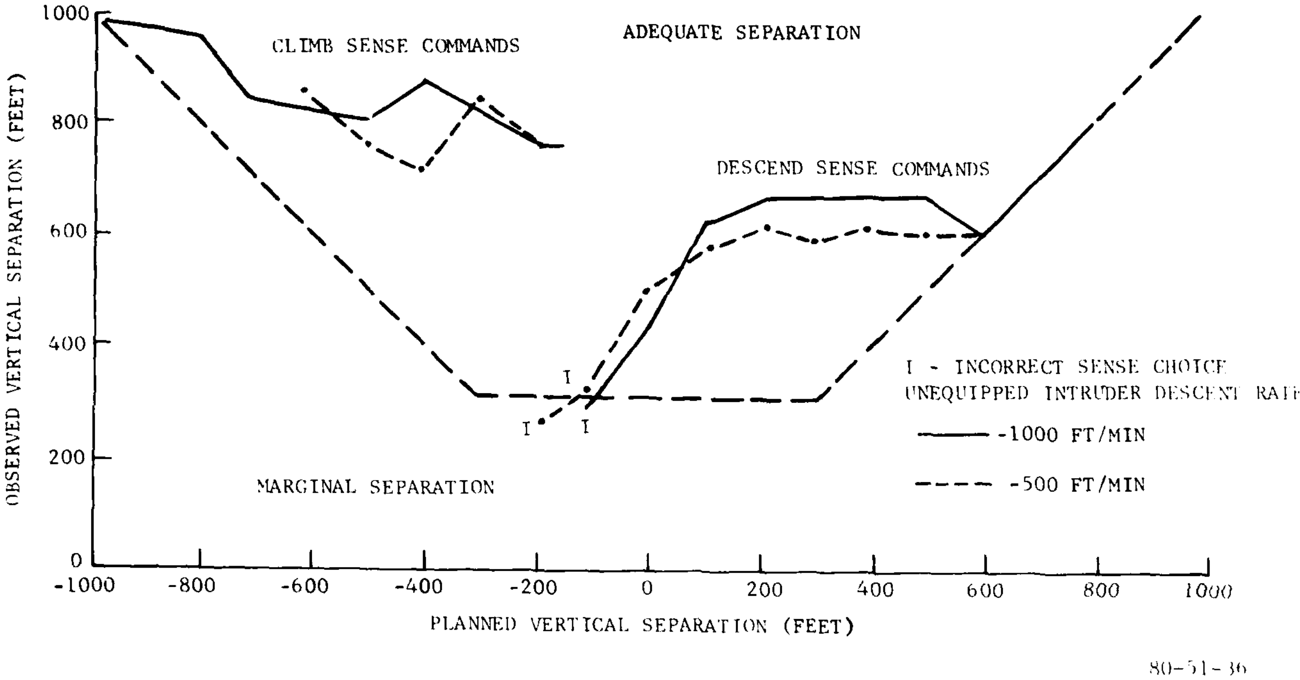


FIGURE 36. VERTICAL SEPARATION FOR LINEAR ENCOUNTERS (LOW VERTICAL RATE FOR UNEQUIPPED INTRUDER)

Performance For Simultaneous Climbs/Descents by Both Aircraft. Two geometries are analyzed. In both cases, the intruder is unequipped. Figure 39 depicts the first geometry. For this case, both aircraft are maneuvering in the same vertical direction. The planned vertical separation at CPA is varied from -1,000 through 1,000 feet in 100-foot increments. In the second geometry (figure 40), the unequipped intruder descends at 1,000 ft/min, while the BCAS aircraft climbs at 600 ft/min. The planned vertical separation at CPA is varied from -1,000 through 1,000 feet in 100-foot increments.

Figures 41 and 42 present the observed vertical separation versus planned vertical separation for each geometry. Adequate separation is observed in all cases.

The results of paired encounters in which both aircraft are climbing are very consistent with the results presented in figure 41. All results confirm that the algorithm performance is excellent for encounters with unequipped threats when both aircraft are maneuvering vertically.

CONCLUSIONS

The analyses of the Active Beacon Collision Avoidance System (BCAS) logic against mode C equipped (ATCRBS) threats using the Fast-Time Encounter Generator (FTEG) yielded the following conclusions.

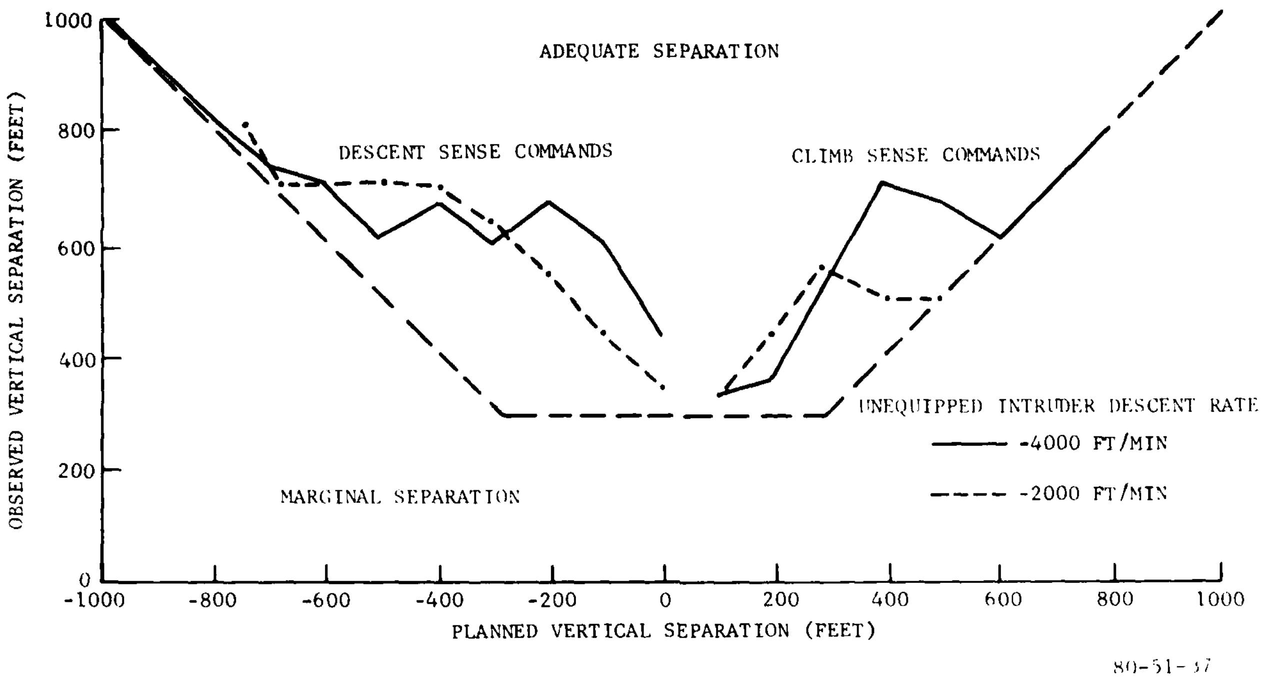


FIGURE 37. VERTICAL SEPARATION FOR LINEAR ENCOUNTERS (HIGH VERTICAL RATE FOR EQUIPPED INTRUDER)

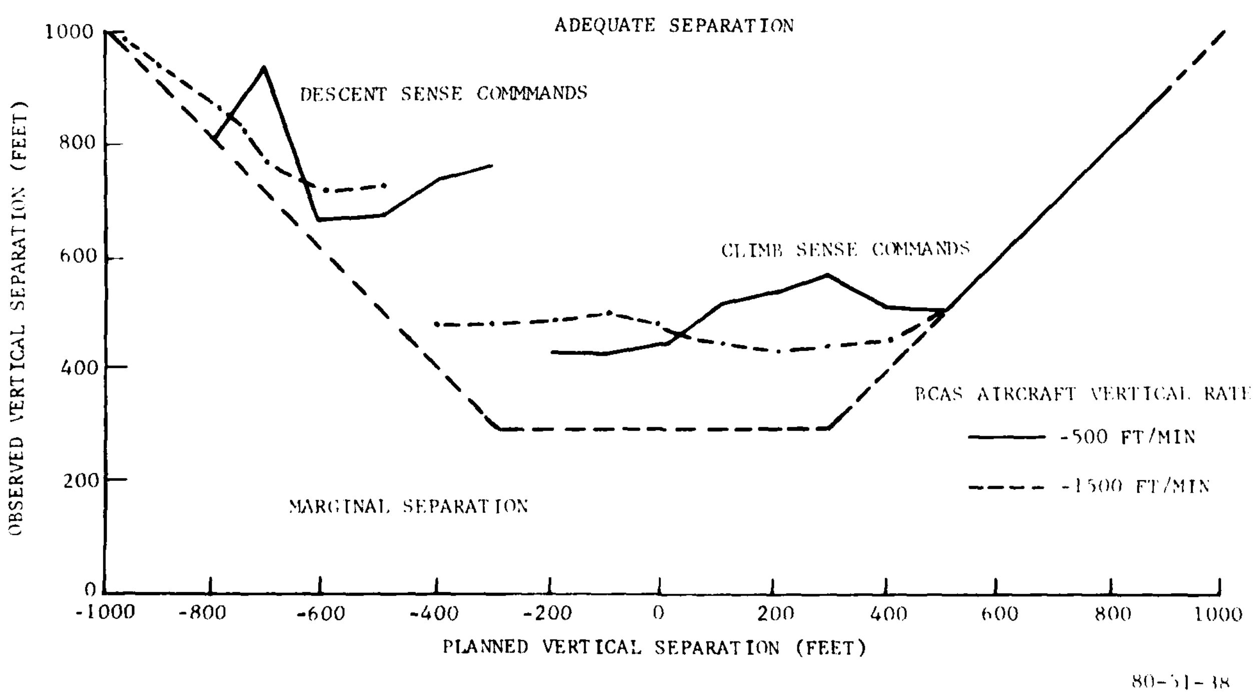


FIGURE 38. VERTICAL SEPARATION FOR LINEAR ENCOUNTERS (LOW VERTICAL RATE FOR EQUIPPED INTRUDER)

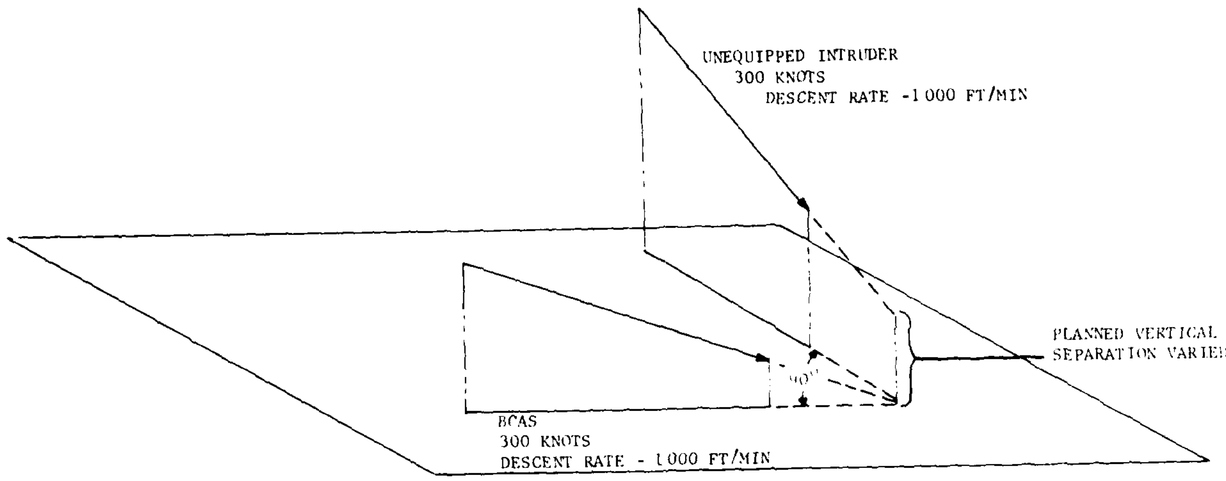
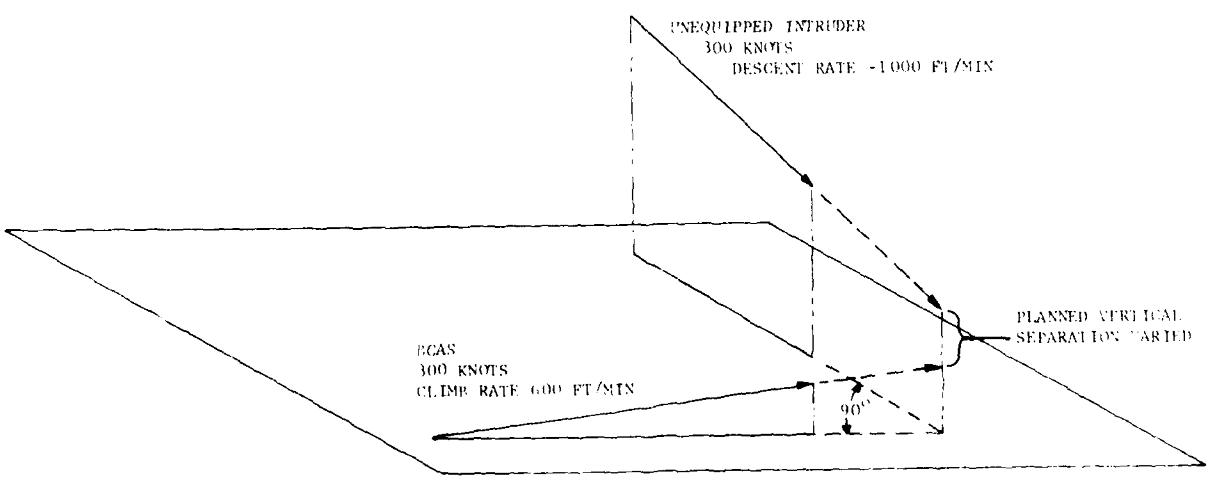


FIGURE 39. BASIC GEOMETRY FOR PARALLEL VERTICAL MANEUVER EVALUATION



FIUGRE 40. BASIC GEOMETRY FOR OPPOSING VERTICAL MANEUVER EVALUATION

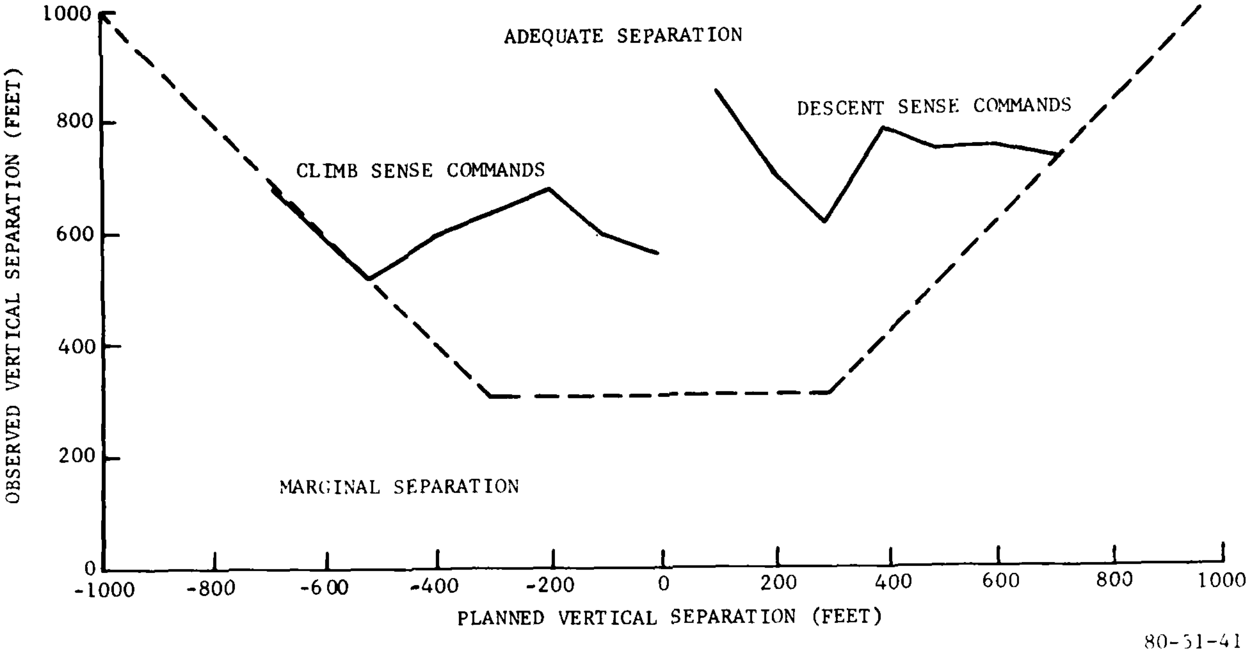


FIGURE 41. VERTICAL SEPARATION FOR PARALLEL VERTICAL MANEUVERS BY AN UNEQUIPPED THREAT

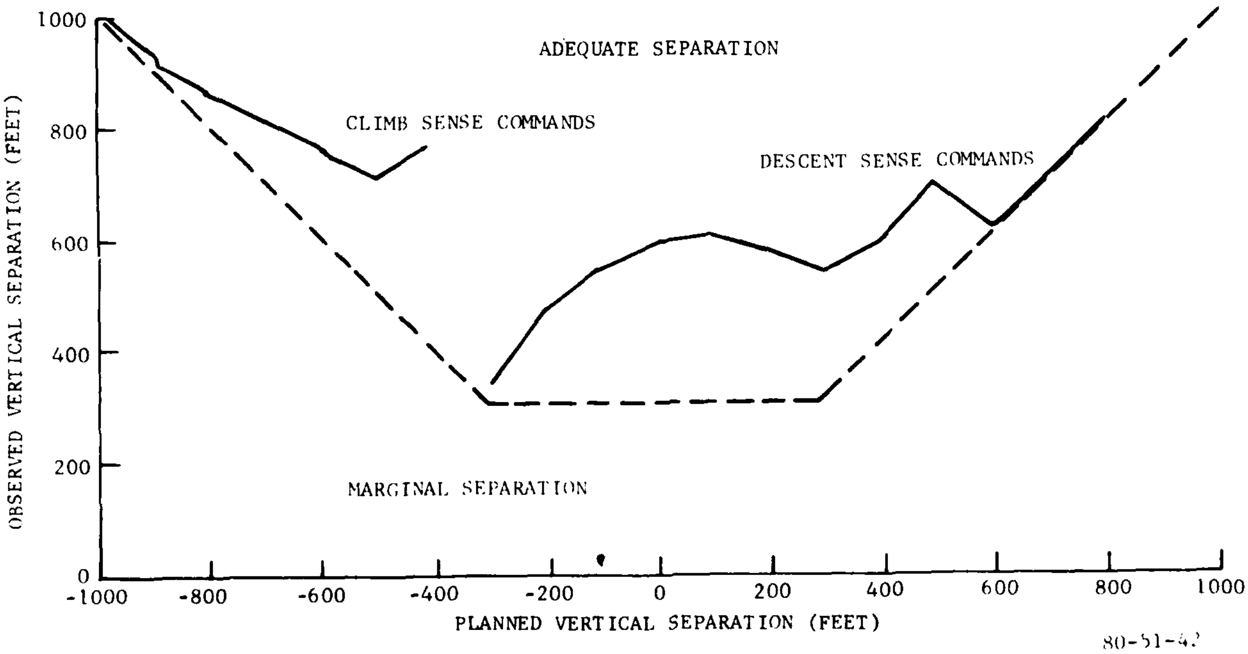


FIGURE 42. VERTICAL SEPARATION FOR OPPOSING VERTICAL MANEUVERS BY AN UNEQUIPPED THREAT

VERTICAL TRACKER PERFORMANCE.

The vertical tracker performance based on the April 1979 logic was unacceptable. In August 1979, based on analysis of results of conflict simulation at the Federal Aviation Administration (FAA) Technical Center, MITRE Corporation changed the vertical tracker algorithm and specified a new tracker β value. These changes resulted in improved vertical tracker performance. Even with improved tracker performance, the tracked vertical rate still oscillates around 0 feet per minute (ft/min) after level off. The determination of command sense based on vertical tracker information can result in an incorrect sense choice due to vertical tracker lags and tracker oscillations. Since sense choice is made on one specific logic cycle, the periods of incorrect sense choice could be reduced by using other than an $\alpha - \beta$ vertical tracker.

Recent flight test results at the FAA Technical Center indicate that random mode C altitude report quantization can result in vertical rate tracker errors. If these errors occur during the period of sense choice for unequipped threats, an incorrect sense choice can result. Further tracking parameter changes may eliminate the problems associated with the tracked altitude excursions. However, it may be necessary to develop a dynamic vertical tracker. A dynamic tracker would make use of the mode C report history.

SENSE CHOICE LOGIC.

The original unequipped sense choice logic contained several flaws which resulted in poor or marginal separation performance. These flaws included a lack of acceleration delay in the sense choice portion of the algorithm, a failure in the sense choice logic to consider the impact of negative values of anticipated maneuver time before closest approach (TESC), a conservative time estimate for projected vertical miss distance (VMD) projections causing positive commands when no commands are required, and poor unequipped intruder sense choice during tail chase encounters. These conditions have been corrected by logic changes. The revalidation of performance following these logic changes, in general, indicated adequate resolution performance.

Vertical rate tracker errors can dominate the measurement of the intruder true vertical rate. Tracked vertical rate errors can exceed 900 ft/min. As a result, sense choice logic modifications now make greater use of current relative vertical position in sense choice for the ATCRBS intruder. These modifications have significantly improved resolution performance.

VERTICAL SPEED LIMIT PERFORMANCE.

In general, the vertical speed limit (VSL) performance is good, irrespective of vertical rate, aircraft velocities, planned vertical separation, and crossing angle. The major problems found in the unequipped intruder logic pertaining to VSL's were (1) short duration VSL's, (2) generation of more than 1,000 feet of vertical separation or unnecessary alarms for encounters involving high vertical rates or more than 1 nautical mile planned horizontal separation, and (3) command transitions due to tracker noise. The major changes to the VSL logic in previous BCAS algorithms corrected previous performance faults. The inclusion of an aircraft response acceleration model in the selection of the VSL magnitude has helped to prevent VSL magnitude oscillations.

Vertical rate tracker errors cause unnecessary changes from 500 ft/min VSL alarms to negative commands. This condition usually occurs when the BCAS aircraft's vertical rate is less than 1,000 ft/min and the ATCRBS threat is nearly level. Although a larger VSL alarm magnitude set caused less deviation in the vertical profile of BCAS aircraft with vertical rates in excess of 2,500 ft/min, a change in the magnitude of the VSL alarms is not recommended because the larger VSL magnitude set doubled the number of alarm transitions.

GENERAL PERFORMANCE.

In general, BCAS performance for paired encounters involving an unequipped aircraft is excellent. The logic effectively handles abrupt horizontal maneuvers and all linear encounters involving both high and low vertical rates. BCAS cannot always prevent collisions in encounters that involve abrupt vertical acceleration.

ADVANTAGES OF PARTIAL POSITIONAL DATA.

Improvement in collision avoidance performance can be expected if partial positional data augment the BCAS commands being displayed. This is especially true when an ATCRBS threat accelerates vertically during or immediately following command sense selection.

RECOMMENDATIONS

Based on this analysis of Active Beacon Collision Avoidance System (BCAS) logic performance evaluation for mode C equipped (ATCRBS) threats, the following recommendations are made:

1. The modifications of the Active BCAS Logic identified and validated in this report (chronologically listed in appendix B) should be implemented in the Active BCAS collision avoidance logic.

2. The error characteristics of $\alpha - \beta$ vertical tracking and the impact of these errors on the unequipped intruder sense choice logic suggest that a more responsive vertical tracker be developed.

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APPENDIX A

DESCRIPTION OF THE FAST-TIME ENCOUNTER GENERATOR

FAST-TIME ENCOUNTER GENERATOR.

The Fast-Time Encounter Generator (FTEG) provides a dynamic representation of aircraft flight profiles. This allows for (1) the analysis of the Beacon Collision Avoidance System (BCAS) algorithm and (2) the evaluation of the BCAS algorithm logic in both an error-free and error-degraded environment. The FTEG models the dynamic interaction between algorithm command generation and the aircraft response. The FTEG allows rapid replication of desired aircraft and algorithm conditions across a wide range of experimental conditions.

The FTEG generates up to 20 target reports to the BCAS surveillance function, each logic cycle, through establishment of user-defined aircraft encounter scenarios. The FTEG data set used to establish a scenario consists of:

1. Flight plans for all aircraft.

2. Closest point of approach miss distance (ΔX, ΔY, ΔZ) between all aircraft.

3. BCAS equipage of all aircraft.

4. Aircraft vertical rate threshold parameters.

5. Error condition.

The FTEG allows the user to initially define the desired aircraft geometries at the closest point of approach. Through the fast-time simulation of desired scenarios, the FTEG provides the means to rapidly evaluate the BCAS conflict resolution performance. Selected conflict information is extracted from the BCAS algorithm to create line printer output and Cal-Comp™ plots to allow the analyst to "see" algorithm performance.

The FTEG's error modeling capability permits evaluation of error-degraded algorithm performance. Simulation in an error-degraded environment is performed through modeling the following surveillance, measurement, and tracking errors:

Transponder delay.

Altitude correspondence error.

(BCAS) aircraft altitude error.

altitude error.

ment (acquisition) delay.

reports.

To allow for simulation in an error-free or error-degraded environment, each aircraft in the scenario has an error code which specifies the error mode (free or degraded). The input errors, if present, are applied to the input measures in the BCAS surveillance function.

The FTEG provides for the simulation of the dynamic interaction between the aircraft response and BCAS algorithm command generation. All BCAS equipped aircraft will follow the predefined flight plans until a BCAS command is generated. Unequipped aircraft will always fly the predefined flight paths. To facilitate aircraft response to the BCAS commands, the FTEG distinguishes between advisory and effective commands. An advisory is an algorithm-generated alarm which does not conflict with the aircraft's current flight plan. An example is a "don't descend" command while the aircraft is in a climb. Effective commands are those which do conflict with the current flight plan. Processing is discontinued for all advisories as no flight plan change is generated. The applicable flight plan change is generated for effective BCAS commands. Table A-1 lists the Active BCAS commands and the aircraft response.

All aircraft respond to the positive commands by maneuvering in the desired direction (sense) until the command is dropped or changed, or until the aircraft reaches the desired response rate. Two FTEG parameters, which may vary between simulations, are required to maneuver aircraft in response to the generated BCAS commands. The first is the positive command response rate which specifies the change in vertical rate to be achieved when an aircraft receives a positive BCAS command. The second is the acceleration parameter which specifies the change of rate of the aircraft in attaining the desired vertica' rate. Given a BCAS positive command, the aircraft will accelerate at the rate specified by the parameter value until the desired vertical rate is attained or the command is dropped or changed. The BCAS advisories (negative and vertical speed limit commands) intrinsically determine the desired vertical rate (see table A-1). In attaining this vertical rate, the aircraft will accelerate (or decelerate) at the specified acceleration parameter value. Given an effective BCAS advisory the aircraft will accelerate (or decelerate) until the desired vertical rate is achieved or the command is dropped or changed. To simulate pilot response delay, the FTEG allows for a variable response delay selected from a 1- to 14-second truncated gamma distribution or a user-chosen pilot-response delay which will remain constant throughout the simulation. Generally, in the analysis of the BCAS algorithm, pilot response was held fixed at 5 seconds to reduce additional performance variation.

The FTEG has the capability to simulate an individual scenario up to 1,000 times per computer run. This capability was developed to aid in the analytical efforts of algorithm performance in an error-degraded environment. It is in this environment that algorithm performance may vary given identical scenarios. A more powerful feature of the FTEG is the ability (1) to modify certain parameters of the FTEG scenario data set and (2) to perform a simulation with the updated scenario. The FTEG can simulate up to 256 related scenarios per computer program. This process aids in the analytical effort through identification of specific flight data corresponding to a breakdown in BCAS algorithm performance. This provides a sensitivity analysis capability.

TABLE A-1. BCAS COMMANDS AND AIRCRAFT RESPONSE

COMMAND MEANING	SENSE OF COMMAND	AIRCRAFT CLIMBING	AIRCRAFT DESCENDING	AIRCRAFT LEVEL
0 - No Command		NE*	NE	NE
1 - No Climb	Descend	Level Off	NE	NE
2 - No Descent	Climb	NE	Level Off	NE
3 - Not Used	N/A	N/A	N/A	N/A
4 - Climb	Climb	Increase Climb to Present Rate + Response Rate***	Climb at Response Rate	Climb at Response Rate
5 - Descend	Descend	Descend at Response Rate	Increase Descent to Present Rate + Response Rate	Descend at Response Rate
6** - Limit climb to 2,000 ft/min	Descend	Climb $\leq$ +2,000 ft/min	NE	NE
7** - Limit climb to 1,000 ft/min	Descend	Climb $\leq$ +1,000 ft/min	NE	NE
8** - Limit climb to 500 ft/min	Descend	Climb $\leq$ +500 ft/min	NE	NE
9** - Limit descent to 500 ft/min	Climb	NE	Descend $\leq$ -500 ft/min	NE
10** - Limit descent to 1,000 ft/min	Climb	NE	Descend $\leq$ -1,000 ft/min	NE
11** - Limit descent to 2,000 ft/min	Climb	NE	Descend $\leq$ -2,000 ft/min	NE

* No effect (NE) on aircraft vertical rate.

** These are vertical speed limit commands (VSL's). Response to these commands is effected only if the aircraft exceeds the VSL rate.

*** Response rate is defined by the user. No vertical rate exceeds aircraft type limiting values defined in the FTEG input.

APPENDIX B

CHRONOLOGICAL REVIEW OF MODE C EQUIPPED (ATCRBS) THREAT PERFORMANCE DEFICIENCIES

This appendix presents the chronological review of logic deficiencies for mode C equipped (ATCRBS) threats. Each deficiency is briefly identified. Page numbers refer the reader to portions of the report which describe the deficiency and tested solutions in fuller detail.

LOGIC DEFICIENCIES

PROBLEM DESCRIPTION	MODIFICATION	PAGE
1. The larger of two threat volumes was not always selected properly.	1. Sensitivity performance level selection has become a function of the detection and resolution logic model DRACT (May 1979).	9
2. The coordination logic did not initiate the storage of threat track block data.	2. The coordination module COORD was modified to initiate the storage of track block data (May 1979).	8
3. Poor performance of the tracker caused incorrect sense choices, inconsistent command patterns, and unacceptable separation for ATCRBS threats.	3. The β parameter has been changed twice. Other logic changes have also been added to control the problem of incorrect sense choice. These modifications have not totally resolved the problems (July, August 1979; June 1980).	9
4. The ATCRBS sense choice logic did not consider the impact of negative values of TESC, the anticipated maneuver time before closest point of approach (CPA).	4. Logic modifications were made to base selection of command sense on relative positive when TESC is negative (July 1979).	24
5. Sense choice logic for ATCRBS threats failed to allow for the time delay to achieve the vertical rate change in the modeled response.	5. An acceleration model was added to the ATCRBS sense choice logic (August 1979).	21

LOGIC DEFICIENCIES

PROBLEM DESCRIPTION	MODIFICATION	PAGE
6. The projected vertical miss distance (VMD) estimate is a signed value; positive commands can result when none are required.	6. The absolute value of VMD is checked to determine if positive commands are necessary (August 1979).	27
7. The logic used a conservative projection of vertical miss distance which generated unnecessary positive commands when large negative values of vertical miss distance actually existed.	7. The projection time for threat detection TVPCMD increased from 25 to 35 seconds. (August 1979). A new alarm filter using VMD imformation was added. This filter compares the projected range at time of coaltitude (January 1980). Very recently, major modifications of the VMD logic have been made to control positive alarms (July 1980).	27
8. Vertical tracker noise and aircraft response caused secondary vertical speed limit (VSL) commands of 1-second duration to occur. In some encounters a cyclic pattern of 1-second VSL commands are observed.	8. Modification of the logic requires VSL commands to be displayed for a minimum of five seconds (July 1979).	38
9. For near level-flight tail chase encounters with an ATCRBS threat, incorrect sense choice may result.	9. Sense choice logic for ATCRBS threats was modified so that when vertical rates are low (<300 ft/min) sense choice is based on relative position (November 1979).	30
10. If ATCRBS threats with high vertical rates decelerate just prior to sense choice selection, Beacon Collision Avoidance System (BCAS) commands which reduce separation may often result.	10. The logic now provides partial positional data (PPD) on threat aircraft (January 1980). Additional vertical tracker improvements are under study to limit incorrect sense choice selection.	32

APPENDIX C

ACTIVE BEACON COLLISION AVOIDANCE SYSTEM (BCAS) LOGIC IMPLEMENTATION

BCAS ALGORITHM.

The Fast-Time Encounter Generator (FTEG) provides aircraft flight data to the Active Beacon Collision Avoidance System (BCAS) collision avoidance algorithm modules. An interface between the FTEG and BCAS modules simulates the functions of an Active BCAS surveillance tracker. This surveillance routine, SURVEL, provides the means for converting the true FTEG positional measures into the necessary data inputs to the BCAS modules. Several other interface functions are also accomplished in the surveillance routine.

FTEG data is provided to the BCAS surveillance routine every second for each aircraft that is active in the simulation. This data includes:

1. Equipage status of each aircraft in the simulation.

2. True grid position (X,Y,Z) of each active aircraft in the simulation.

3. Current simulation time TCUR.

4. Discrete Address Beacon System (DABS) ID if the aircraft was not mode C equipped (ATCRBS).

The true range rate and relative altitude rate for aircraft in a pair are not directly provided to the BCAS algorithm. For each possible pair combination, SURVEL calculates the range and relative altitude between aircraft in the pair. If BCAS performance in the presence of Active BCAS measurement errors is evaluated, the errors are applied to the input measures before any further processing.

For each pair, estimates of the range rate and the relative altitude rate between aircraft are calculated by the surveillance function. Track files for all possible pairs are then obtained. Using the range rate and altitude rate estimates, coarse track filtering of all possible conflict pairs is then accomplished. The coarse track procedure is not described in the baseline logic document, but is the same one that was used for previous real-time Active BCAS experimentation (reference 4). The coarse track procedure is presented in table C-1.

The Active BCAS evaluation requires the modeling of delayed coarse track establishment and missing track reports. The modeling of track establishment interruptions occurs in SURVEL prior to coarse track filtering. Missing track reports are modeled by interrupting the data flow for a specific equipped aircraft threat pair. Missing track reports are modeled after the pair has passed coarse track. This permits the evaluation of the internal track coasting procedures in the collision avoidance algorithms.

SURVEL performs several data conversions for BCAS. Prior to making any relative altitude calculations, the true aircraft altitudes are converted to mode C altitude reports. The mode C altitude reports form the basis for all aircraft altitude data manipulations. The slant range from the reference point (0,0,0) is calculated for each aircraft. This permits TROACT to determine the proper threat threshold sensitivity performance level for each equipped aircraft.

The BCAS logic requires a desensitization method for its threshold parameters. The threat thresholds which identify the BCAS protection volume must be reduced at some point along the arrival path of an aircraft to a terminal which would permit adequate collision avoidance protection without generating an unacceptably high number of alarms. This is accomplished by defining five levels of BCAS threat detection and resolution logic with different threshold parameters for each performance level. As the performance levels increase from 1 to 5, the threshold parameters become more sensitive, thereby increasing the protection volume around each BCAS equipped aircraft. At the time of the evaluation, the following BCAS desensitization scheme was in use: BCAS is shut off in performance level 1. At performance level 2, BCAS tracks the intruder, but all resolution logic is blocked. BCAS protection is available only at levels 3, 4, and 5. The performance level that applies to a particular aircraft is based on the aircraft's altitude and range from a radar beacon transponder (RBX) or sensitivity control unit (SCU). Figure C-1 depicts the performance level boundaries used in the analysis. A later change to this desensitization scheme permitted the identification of two additional altitude strata, AOUTER and AINNER, to further desensitize BCAS performance in the terminal area. Due to the late addition of this desensitzing altitude strata, an evaluation of this new desensitization scheme was not performed. The values of the significant BCAS parameters for each performance level are shown in table C-2.

In order to evaluate BCAS performance, the resulting BCAS commands had to be interfaced into the FTEG flight simulation modules. The BCAS commands are returned to the FTEG in a numerical code form. The codes appear throughout this report in the documentation of the results. The possible BCAS commands and their numerical codes are shown in appendix A, table A-1.

An FTEG executive routine, BCASCNT, controls the logic flow between the various BCAS logic modules. Since the FTEG can simultaneously model the flight of up to 20 different equipped aircraft, this requires that the BCAS logic be executed each second for each equipped aircraft. To support this multiple aircraft simulation process, the high level BCAS logic flow chart (as shown in the baseline logic document) was modified slightly. To ensure proper coordination, all tracking and resolution logic is first executed for all equipped aircraft. This provides the necessary data that is needed prior to exercising the coordination logic, multiple aircraft resolution logic, and the display logic. This double loop process is exercised once a second. Since the FTEG is a discrete time simulation system, this high level flow modification does not influence the performance of BCAS. The high level logic flow used in this evaluation is presented in figures C-2 and C-3.

The BCAS air-to-air coordination procedures are the same as those shown in reference 1. Coordination with equipped threats requires the simulation of interrogation messages in the COORD module. These messages are received and manipulated by the RCV module for the equipped threat. Coordination requires the manipulation of the CIR "D" field arrays as shown in the baseline document.

TABLE C-1. BCAS COARSE TRACK PROCEDURE

	TAUV≤75 sec RZ<4,000 feet	TAUV≤75 sec RZ>4,000 feet	TAUV≥75 sec RZ<4,000 feet	TAUV≥75 sec RZ>4,000 feet
R<3 nmi TAUR≤75 sec	P	P	P	F
R<3 nmi TAUR>75 sec	P	P	P	F
R≥3 nmi TAUR≤75 sec	P	P	P	F
R≥3 nmi TAUR≤75 sec	F	F	F	F

R = Range RZ = Relative Altitude
RD = Range Rate RZD = Relative Altitude Rate
TAUR = -R/RD TAUV = -RZ/RZD
TAUR = 76 if RD ≥ 0 TAUV = 76 if RZD ≥ 0
P = Pass this pair to algorithm processing if either aircraft is equipped.
F = No potential conflict. Do not pass this pair.

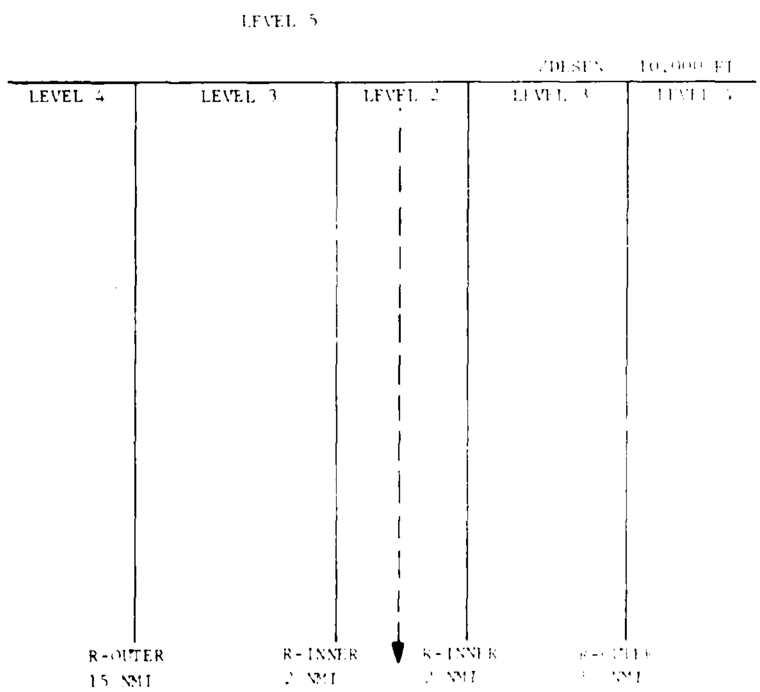

FIGURE C-1. ACTIVE BCAS DESENSITIZATION ZONE

TABLE C-2. ACTIVE BCAS PARAMETER SETTINGS

Symbol	Definition	Level	Value
ACCEPT	Vertical threshold for credibility test when intruder selects imcompatable maneuver.	ALL	400 ft
ALFAR	Tracking constant for range	ALL	0.4
ALFAZ	Tracking constant for altitude	ALL	0.4
ALIM	Altitude threshold for choice of positive or negative command	5 4 3	440 ft 340 ft 340 ft
ALPC	Lower boundary for high altitude airspace	5	18,000 ft
ALUH	Lower boundary for ultrahigh altitude airspace	5	29,000 ft
ASEPH	High altitude positive command threshold	5	640 ft
ASEPU	Ultrahigh altitude positive command threshold	5	740 ft
ATERN	Altitude threshold below which descent commands are not used when radar altimeter input is available	3, 4	500 ft
BETAR	Tracking constant for range rate	ALL	0.15
BETAZ	Tracking constant for altitude rate	ALL	0.10
BUSMAX	Limit to number of busy replies to coordination attempts	ALL	20
CLMRT	Assumed climb escape rate	ALL	16.67 ft/sec
CORR	Threshold for positional correlation of ATCRBS	ALL	6.00
DESRT	Assumed descent escape rate	ALL	-25 ft/sec
DMOD	Modification distance applied to tracked range	3 4 5	0.1 nmi 0.3 nmi 1.0 nmi
EITHER	Threshold for accepting either climb or descent	ALL	150 ft
HI	Divergence threshold at which commands are inhibited	ALL	0.00278 nmi^2/sec
INTMAX	Limit of coordination interrogation attempts	ALL	8
RDTHR	Range rate threshold used to compute range tau during parallel flight	ALL	0.00167 nmi/sec
TDROP	Time required without reported data to drop a track	ALL	10 sec
TLARGE	Large positive number	ALL	1,000
TMIN	Minimum time for display of command	ALL	5 sec
TRTHR	Threshold applied to range tau for threat detection	3 4 5	30 sec 25 sec 30 sec
TVPCMD	Look-ahead time for altitude detection	3 4 5	45 sec 40 sec 40 sec
TVPESC	Look-ahead time for altitude resolution	3 4	30 sec [illegible]

			-25 ft/sec
DMOD	Modification distance applied to tracked range	3	0.1 nmi
		4	0.3 nmi
		5	1.0 nmi
EITHER	Threshold for accepting either climb or descent	ALL	150 ft
HI	Divergence threshold at which commands are inhibited	ALL	0.00278 nmi^2/sec
INTMAX	Limit of coordination interrogation attempts	ALL	8
RDTHR	Range rate threshold used to compute range tau during parallel flight	ALL	0.00167 nmi/sec
TDROP	Time required without reported data to drop a track	ALL	10 sec
TLARGE	Large positive number	ALL	1,000
TMIN	Minimum time for display of command	ALL	5 sec
TRTHR	Threshold applied to range tau for threat detection	3	30 sec
		4	25 sec
		5	30 sec
TVPCMD	Look-ahead time for altitude detection	3	45 sec
		4	40 sec
		5	40 sec
TVPESC	Look-ahead time for altitude resolution	3	30 sec
		4	30 sec
		5	35 sec
TVTHR	Threshold applied to vertical tau for threat detection	3	30 sec
		4	25 sec
		5	30 sec
TV1	Time delay provision for log in response to commands	ALL	5 sec
VACCEL	Assumed escape vertical acceleration	ALL	8 ft/sec^2
V2000	Threshold for 2,000 ft/min vertical speed limit (VSL)	ALL	33.33 ft/sec
V1000	Threshold for 1,000 ft/min VSL	ALL	16.67 ft/sec
V500	Threshold for 500 ft/min VSL	ALL	8.33 ft/sec
ZDTHR	Altitude rate threshold used in threat detection	3	-30 ft/sec
		4	-30 ft/sec
		5	-25 ft/sec
ZTHR	Immediate altitude threshold used in threat detection	ALL	750 ft
ZTHRH	High altitude threshold for threat detection	5	850 ft
ZTHRU	Ultrahigh altitude threshold for threat detection	5	950 ft
ZDLVL	Vertical rate limit below which current altitudes are used for maneuver sense determination	ALL	5 ft/sec

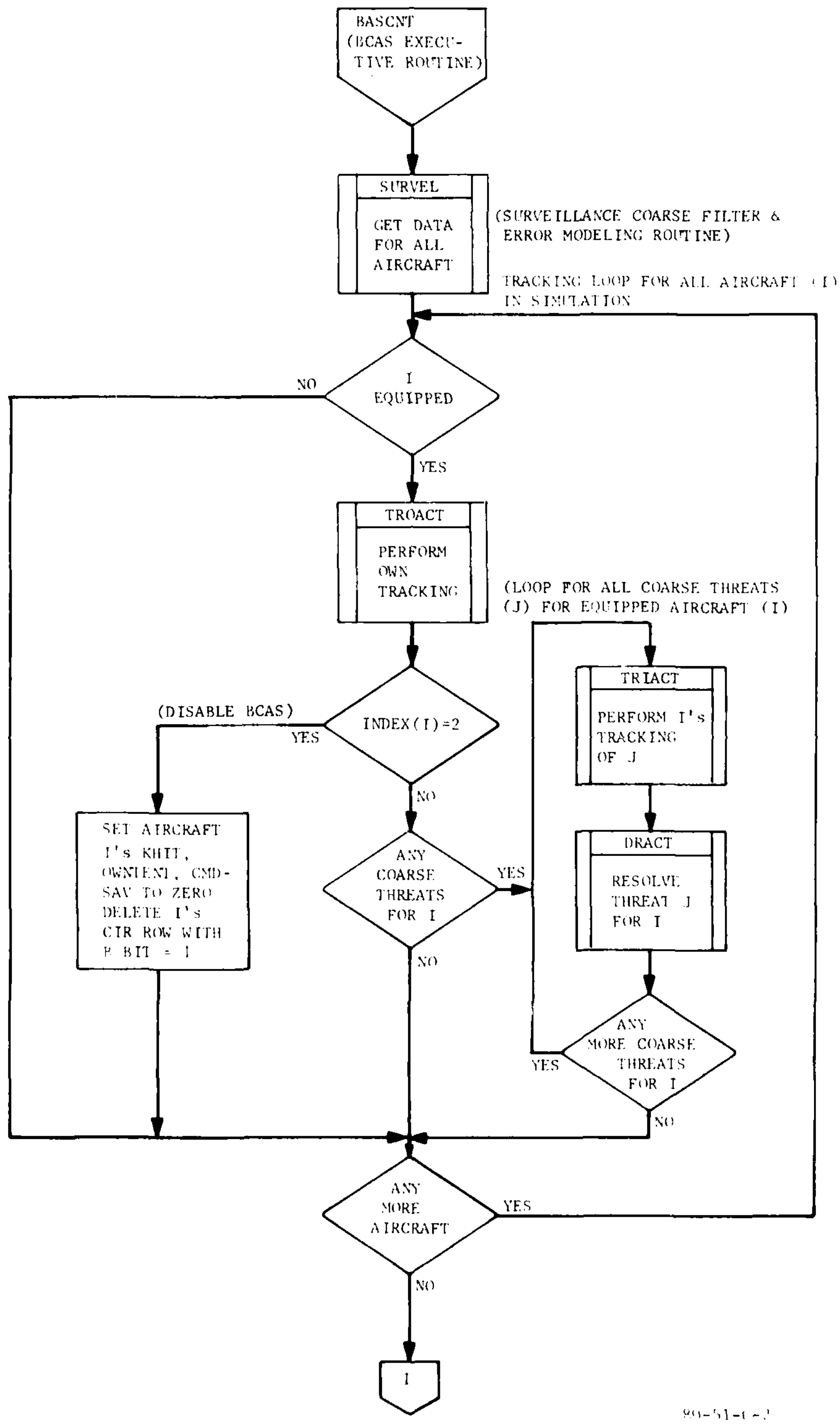

FIGURE C-2. HIGH LEVEL BCAS TRACKING AND RESOLUTION FLOWCHART

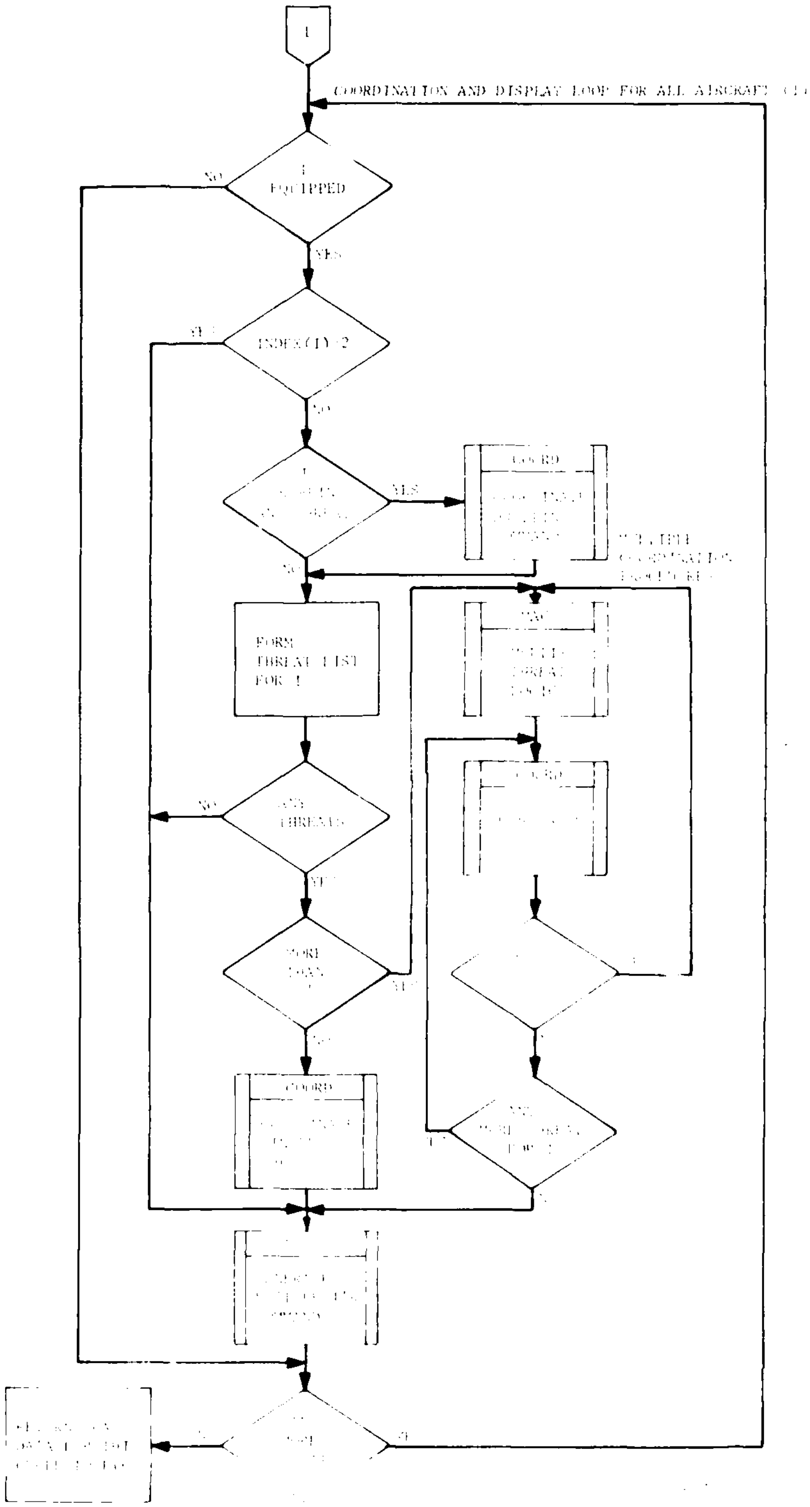

FIGURE C-3. HIGH LEVEL BCAS COORDINATION AND DISPLAY FLOWCHART

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